Quantitative Soil-Landscape Modelling in North Otago, South Island, New Zealand

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Abstract of a thesis submitted in partial fulfilment of the requirements for the Degree of Master of Applied Science

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Digital Elevation Model (DEM), Global Positioning System (GPS) and Geographic Information System (GIS) technologies can be used to improve soil survey method and soil resource information systems, and to explicitly define soil-landscape models (SLMs) in a quantitative manner. Soil data can be more realistically modelled and represented in a semicontinuous manner rather than using chloropleth maps. The aim of the study was to develop quantitative SLMs for a part of the North Otago downlands, with three objectives: 1) to replicate mapping rules used for a 1:50,000 soil map of North Otago (qSLM 1), 2) to map soil taxonomic units (STUs) based on a new dataset from a randomised-stratified sample of soil profiles observed from auger borings (qSLM 2) and 3) to investigate relationships between A horizon percent organic C and N and parent materials, terrain attributes and microclimate.

Discriminant Function Analysis (DFA) used training data from 1) a randomised subsample (n=100) of each Soil Mapping Unit (SMU) of the 1:50,000 map for qSLM 1 and 2) 145 field sample points allocated to predefined STUs for qSLM 2. Digital terrain attributes derived from a 25 m DEM (elevation, aspect, slope, profile and plan curvature, wetness and stream power indices) were used as variates in the DFA. Slope, profile curvature and stream power index were the most useful terrain attributes for discrimination between SMUs in qSLM 1 and success of DFA-derived classification functions ranged 39-56% among lithological units. Stream power index, slope, upslope area and plan and profile curvature were the most useful terrain attributes for qSLM 2, with overall classification success 51%.

The mapping procedure for qSLM 1 and qSLM 2 consisted of allocating 25 m grid cells to SMU or soil series, respectively, on the basis of discriminant function scores. For a given grid cell of the map, discriminant function scores were calculated from the terrain attribute values generated by intersecting that grid cell with the terrain attribute grids. The grid cell was assigned to the SMU (qSLM 1) or STU (qSLM 2) whose associated discriminant function produced the highest score. Correspondence between predicted SMUs of qSLM 1 and the original 1:50,000 map is 39% averaged across all SMUs (range 8-93%). When considered with respect to success in predicting soil taxa at the 145 field sites the 1:50,000 map performed appreciably better (54%) than qSLM 1 (39%). Some STUs were predicted successfully enough by qSLM 1 to justify using it to extrapolate to unmapped areas of similar geology, physiography and loess deposition regime. qSLM 2 had no independent data set, and comparison with the original 1:50,000 soil map was not considered appropriate because the two mapping approaches operate at much different resolutions of landform. Both qSLM 1 and qSLM 2 produced maps with much smaller grain size (characteristic delineation) than the original 1:50,000 soil map. The patterns mirrored landform elements and appeared realistic. It was concluded that qSLM 1 rules defining the spatial distribution of some soils could serve as the basis of further modelling and extrapolation. qSLM 2 is based on more objective data, yet requires further field data for testing its validity. DEMs, GPS and GIS show potential for further detailed modelling of soil types and properties in North Otago.

A horizon percent organic C and N values (n=175) were highly correlated (R^2=0.94). There were significant differences in mean C and N values between parent materials ($P < 0.001$) but classification by parent material explained only 24% and 29% variance in C and N values, respectively. Digital terrain attributes explained only 6% and 5% of variance in C and N values, respectively. Lowest summer rainfall microclimate data explained only 4% and 5% of C and N variance, respectively. The poor correlation between %C or %N and terrain attributes precluded a SLM being developed on the basis of those attributes. A SLM based on parent material alone could have been produced but, generally, variances of %C and %N within parent materials were sufficiently high to make this of little value.

Key words: Digital Elevation Model, Global Position System, Geographic Information System, Discriminant Function Analysis, digital terrain attributes, soil mapping unit, soil taxonomic unit, qSLM 1, qSLM 2, A horizon percent C and N.

Table of Contents

List of Abbreviations

DEM	Digital Elevation Model (DEMs *pl.*)
DFA	Discriminant Function Analysis
ESS	Earth Surface System
GIS	Geographic Information System(s)
GPS	Global Positioning System
NIWA	National Institute of Water & Atmospheric Research
NZGC	New Zealand Genetic Classification
NZMG	New Zealand Map Grid
NZSC	New Zealand Soil Classification
qSLM 1	Quantitative Soil-Landscape Model 1 – based on pre-existing map data.
qSLM 2	Quantitative Soil-Landscape Model 2 – based on field data.
SLM	Soil-Landscape Model (SLMs *pl.*)
SLU	Soil-Landscape Unit (SLUs *pl.*)
SMU	Soil Mapping Unit (SMUs *pl.*)
STU	Soil Taxonomic Unit (STUs *pl.*)

List of Figures

List of Tables

List of Appendices

Chapter 1

Introduction

1.1 General Introduction

The scientific study of soils is a significant example of the convergence of basic and applied research. Soils, perhaps more so than any other terrestrial (as opposed to marine) phenomena, are capable of providing insight into fundamental earth-surface processes, while at the same time providing the essential life-support mechanism for human sustenance and survival. The endeavour to understand the nature and distribution of soil phenomena is therefore of prime academic interest to pedologists in particular, and of direct value to society in general.

Soil resource information is vital for land use planning at the local, regional and national scales, and accurate soil resource information is required to encourage sustainable land use and environmental protection (Basher, 1996). Basher (1996) stated that information on soil resources would continue to be important for planning sustainable management of land resources through matching land use with soil type. For instance, in agricultural and horticultural production, readily available quality soil resource information allows land managers to address issues concerning soil fertility in order to maximise production and minimise costs and environmental degradation.

These practical concerns are addressed by pedological science, which seeks to understand the nature and distribution of soil phenomena. This knowledge has directly applicable benefits, and practical concerns provide the gateway to more complex and detailed research investigating fundamental aspects of landscape processes and history. A focus on the practical concerns of land managers can create the first link in what Bouma (2001) has described as *research chains* in which applied research projects provide a focus for basic research with increasing complexity at a range of spatial and temporal scales. Research chains also include the incorporation of different levels of knowledge – from farmer to pedologist. The present work is a link in the research chain investigating the natural resources of North Otago, and defines quantitative soil-landscape models (SLMs) of part of North Otago based on pre-existing soil data and new data gathered in this study. This work will contribute to the GrowOtago project, an initiative developed by Otago regional government in conjunction with various Crown Research Institutes to map in detail climate and land resources in order to catalyse regional development through identifying new options for primary production. The quantitative modelling of soil resources in North Otago is an integral component of this project, and the present work presents a research approach applicable to other areas in the Otago region.

Presented below (Sections 1.1.1, 1.1.2 and 1.1.3) are brief descriptions of the development and nature of pedological science. The remainder of this Chapter describes the theoretical context of quantitative soil-landscape modelling in North Otago (Section 1.2), followed by the aims and objectives of the study (Section 1.3). Chapter 2 is a review of the location, climate, geology and physiography of the study area, along with a review of the soils present in the area. Chapter 3 describes the soil, geological and digital terrain data used in the development of quantitative SLMs for the present work. Chapter 4 is a description of quantitative Soil-Landscape Model 1 (qSLM 1), a model of the study area based on pre-existing soil, geological and digital terrain data. Chapter 5 is a description of quantitative Soil-Landscape Model 2 (qSLM 2), a model of the study area based on field research, digital terrain and geological data. Chapter 6 describes analysis of organic carbon and nitrogen content of soils in the study area based on the sample points used in qSLM 2. Chapter 7 is a synthesis and summary of the approaches used here, and evaluates the success of the quantitative soil-landscape models.

1.1.1 The Evolution of Pedological Science

The origins of human thought regarding the nature and distribution of soils are lost in antiquity. In favourable regions, the climatic transition from the Pleistocene to the Holocene and the subsequent evolution of agriculture marks a period in history where previous human patterns of hunting, gathering and shifting cultivation were gradually transformed into more permanent and settled systems of food production (Diamond, 1998). This profound historical development led to a greater familiarity with the spatial variation in those soil properties of direct value to agricultural production. As agriculture, cities and civilisations expanded, folk knowledge of soil landscapes was encapsulated in language and tradition (Hillel, 1991a; Hillel, 1991b).

With the development of the Western intellectual tradition, the nature and distribution of soils was increasingly examined using the tools and methodologies of science (Glacken, 1973; Krupenikov, 1993; Yaalon and Berkowicz, 1997). The recognition of soils in the nineteenth century as a unique natural body distinct from other earth phenomena freed the study of soils from the previously dominant emphases of geological weathering and agricultural chemistry (Yaalon, 1997), and was essential for the development of pedology as an independent scientific discipline with its own set of operating paradigms (Kuhn, 1970; Hudson, 1992; Tandarich and Sprechen, 1994).

1.1.2 The Philosophy of Pedological Science

Barrow (1992, p.162) emphasised that the universe we observe is the outcome of laws of Nature, and that science is the search for pristine mathematical laws behind the complexity of resulting outcomes. The mathematical description of natural *laws* is most powerful in physics and chemistry. Pedological science, however, like the geological and biological sciences, investigates the *outcomes* of these laws, outcomes that are subject to evolutionary and contingent processes (*i.e.* they are time-dependent). Pedology is therefore not readily amenable to the mathematical formalisations and logical analyses characteristic of physics and chemistry. Pedology is an *historical* science that calls for the testing of competing historical narratives to discriminate between those that best explain the history and spatial nature of particular soil landscapes, a methodology characteristic of modern geomorphology (Church, 1996) and evolutionary biology (Mayr, 2000). Dijkerman (1974) also stated that pedological theories are *informal theories* for they do not follow the rules of formal logic. However, when the complex outcomes of natural laws manifest in soil landscapes, order emerges at certain spatial and temporal scales and is amenable to soil-landscape modelling.

In discussing methodology in pedological science, Wielemaker *et al.* (2001) claimed that soil survey is mainly a deductive process. However, as described by Hillel (1987), pedological research in general is a necessary interplay between deductive (inference from general to particular) and inductive (inference from particular to general) reasoning. Since pedology has developed as an empirical science based primarily on observation (Dijkerman, 1974), the transformation of this body of particular observations into a coherent theoretical framework (*e.g.* the soil-landscape paradigm, see Section 1.2.2 below) has been dependent upon an inductive process of reasoning from the particular to the general. Confidence in this theoretical framework, the soil-landscape paradigm (Kuhn, 1970, and Hudson, 1992), has led to specific hypotheses being constructed and predictions made, reasoning deductively from the general to the particular. These hypotheses are amenable to testing by the traditionally empirical nature of pedological research, and their testing leads to the development of pedological models.

1.1.3 The Nature of Pedological Models

The pedological models of relevance to this study will be discussed in the context of the model classification proposed by Hoosbeek and Bryant (1992). Models are classified according to their relative degree of computation, complexity and level of organisation. The degree of computation and complexity that characterise pedological models along their scale hierarchy is summarised in Figure 1.1 and Table 1.1.

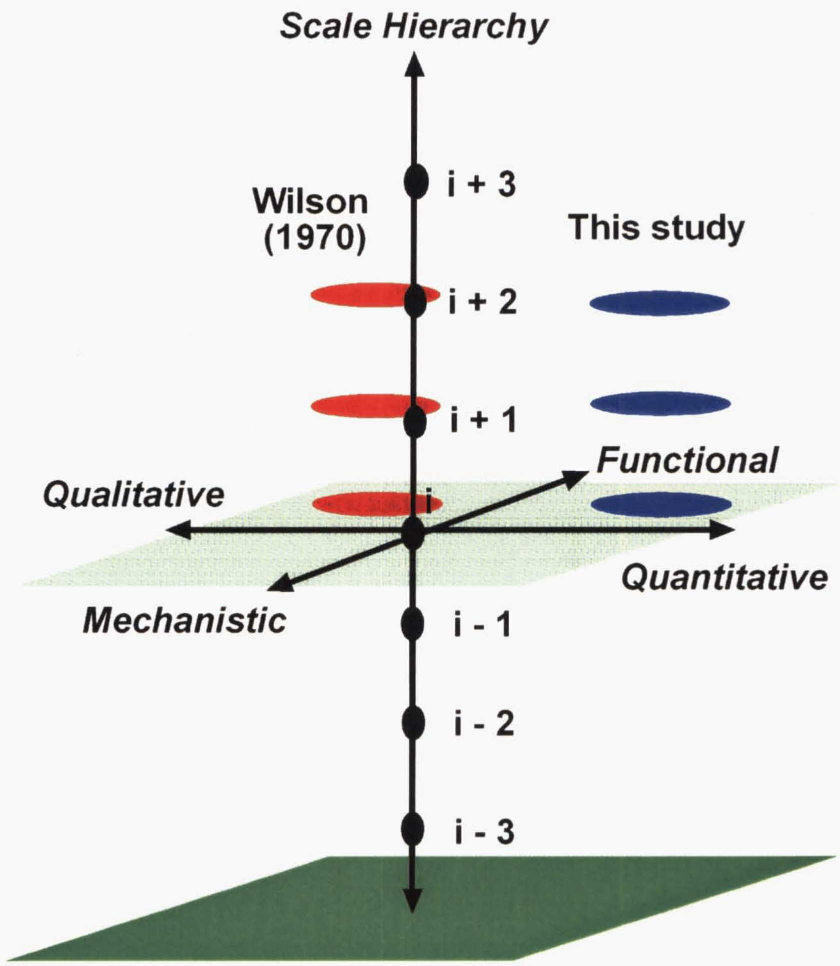


Figure 1.1

Pedological modelling approaches and scale hierarchy of soil systems. See Table 1.1 for explanation of *i*-levels. The levels of soil phenomena covered by the present work and Wilson (1970) are indicated. After Hoosbeek and Bryant (1992).

The relative degree of computation is described by the qualitative-quantitative classification (Figure 1.1). Mental, verbal and descriptive models are placed at the qualitative extreme of the scale, while deterministic or stochastic mathematical models are placed at the quantitative extreme of the scale. Most pedological models fall somewhere between these two extremes (Hoosbeek and Bryant, 1992).

The functional-mechanistic classification describes the complexity of the structure used in the model (Figure 1.1). Models that use a simplified or empirical relation between observed and simulated data without detailing the fundamental processes involved employ a 'black box' approach and are placed at the functional extreme of the scale. These functional models generally comprise capacity and management models, the former simulating changes in quantities without time as a direct variable, the latter providing reasonable answers for resource management without simulating natural systems in detail. Those models that incorporate fundamental mechanisms of the processes involved are placed at the mechanistic extreme of the scale. These mechanistic models are generally comprised of rate and research models, the former using differential equations and iterative procedures to simulate changes in variables as a function of time, the latter used to develop and test hypotheses concerning natural systems (Hoosbeek and Bryant, 1992).

Scale hierarchy describes a model's level of organisation (Figure 1.1 and Table 1.1). As stated by Hoosbeek and Byrant (1992), each level of the hierarchy can be considered a system in itself, viewed as a combination of subsystems at lower levels, or viewed as a subsystem of higher-level systems. Levels on the organisational hierarchy are defined in Table 1.2. Hoosbeek and Bryant (1992) placed the pedon at the central *i*-level on the hierarchy and defined the other *i*-levels according to their ability to represent the nature and variability of certain systems.

The SLMs developed in the present work fall into the quantitative-functional quadrant of Hoosbeek and Bryant's (1992) classification scheme (Figure 1.1), and are focused on positive *i*-level macro-scale phenomena ranging from pedon to catenary scales (Table 1.1). The SLMs are quantitative due to their reliance on statistical methods for their construction, and functional because they do not detail the processes underlying the spatial soil patterns they attempt to define. They are therefore static models that do not incorporate time. In this respect the quantitative SLMs are the same as those qualitative conceptual models of Wilson (1970) for the study area (see Section 2.7, Figure 2.28).

Table 1.1

Scale hierarchy of soil systems and pedological research. The levels of soil phenomena covered by the present work and Wilson (1970) are indicated in blue. Modified after Dijkerman (1974) and Hoosbeek and Bryant (1992).

Level on Scale Hierarchy	System	Examples of Pedological Modelling
i + 3	Soil region	Global phenomena (CO_2 studies)
i + 2	Catena	Soil-landscape modelling. Catchment area budget studies
i + 1	Polypedon	Pedological Modelling as part of a dynamic research
i	Pedon	Dynamics of genetic processes
i – 1	Horizon	Dynamics of horizonation
i – 2	Peds, Aggregates	Micromorphological studies
i – 3	Molecular Interaction	Ion exchange phenomena, complexation of metal ions by organic matter

1.2 Theoretical Context of the Study

1.2.1 The Pedosphere as an Earth Surface System

The soils of the Earth comprise the pedosphere. Phillips (1999), in his study on the complexity, order and scale of Earth-surface phenomena, described the pedosphere as the prototype model of an Earth Surface System (ESS). The characteristic features of this pedospheric ESS are:

- Complex non-linear dynamic interactions exhibiting instability and sensitivity to initial conditions.

- The evolution through time of increasing complexity, within ranges set by external environmental conditions.

- Change in variability (*i.e.* degree of stability versus chaos in the manifestation of non-linear dynamic systems) as a function of scale, with self-organisation and emergent order (Phillips, 1999).

These characteristics of the pedosphere lead to the spatial and temporal complexity exhibited by soil landscapes. As succinctly stated by Wilding (1994):

> Soils are developed along polygenetic pathways, on dynamically evolving landforms under the influence of paleoclimates, in non-uniform parent materials and through combinations of processes.

This suggests that the nature and distribution of pedological phenomena are profoundly influenced by spatial and historical contingency (*e.g.* Phillips, 2001). The recognition of this sensitive dependence upon initial conditions led Phillips (2001) to claim that the historical and spatial contingency of soil landscapes might make broad-scale pedological generalisations difficult, impractical or even impossible. The vagaries of past climatic conditions, the subtleties in changes in parent material, the complexities of landscape evolution; all of these conspire to complicate soil-landscape interpretation. However, given that the manifestation of spatial and historical contingency might dominantly be a matter of scale and that causation and explanation of landscape change might also be scale-dependent (Harrison, 2001), that soil processes act at different intensities or variable relevance at different scales (Thwaites and Schafer, 2000), and that emergent order is a defining characteristic of the pedosphere (Phillips, 1999), it follows that at certain scales order and stability will be manifest in soil landscapes.

The recognition that soil-landscapes exhibit order at certain spatial scales has made possible the development of theoretical constructs to model them (see Section 1.1.3). Church (1996) argued that while the largest spatio-temporal scales are dominated by non-linear contingent landscape evolution reflecting multiple causality and polygenesis, the use of classical deterministic models is valid at smaller spatial scales. This supports the contention of Phillips (2001) that at certain scales a single explanatory principle or set of principles can exist for the majority of pedological phenomena against which exceptions are judged, and that at certain scales pedological phenomena might not be subject to contingency in the context of a particular problem. Thus while pedological systems can display extreme complexity, they are also amenable to the explanatory and interpretive principles of scientific modelling.

In summary, the pedosphere is an extremely complex ESS characterised by spatial and historical contingency, yet can be modelled to varying degrees depending upon the scale of observations and analyses, and the scale of soil phenomena to be modelled (Figure 1.1 and Table 1.1). The empirical investigations of pedological science operating at a range of scales have discerned systematic relationships between soil phenomena and other landscape characteristics, and these are codified in the soil-landscape paradigm.

1.2.2 The Soil-Landscape Paradigm

Hudson (1992), reviewing of the importance of Kuhn's (1970) ideas of scientific paradigms to soil survey, summarised the dominant guiding concept (or group of concepts) of pedological science – the soil-landscape paradigm. For the purposes of the following discussion, the paradigm is explicitly stated here (from Hudson, 1992). The soil-landscape paradigm is composed of five essential concepts:

1. **Within a soil-landscape unit (SLU), the factors of soil formation (see below) interact in a distinctive manner. As a result, all areas of the same soil-landscape unit develop the same kind of soil. In a given soil survey area there is a relatively small number of different SLUs. Individual areas of each unit occur again and again.**

2. **Generally, the more different adjacent areas of two SLUs are, the more abrupt and striking the discontinuity separating them. Conversely, the more similar adjacent areas of SLUs are, the less striking the discontinuity separating them tends to be.**

3. **Generally, the more similar two landscape units are, the more similar their associated soils tend to be. Conversely, very dissimilar SLUs tend to have very dissimilar soils.**

4. **Adjacent areas of different soil-landscape units have a predictable spatial relationship with each other *e.g.* one area will always be located above another in the landscape, or between another and a stream.**

5. **Once the relationship among soils and SLUs have been determined for an area, the soil cover can be inferred by identifying the characteristic SLUs. The soil is examined directly only as needed to validate this relationship.**

The soil-landscape paradigm is the fundamental conceptual framework upon which pedological science in general and soil surveys in particular are constructed, and is the legacy of two interwoven threads of traditional pedological research: the soil-forming factors and pedogeomorphology. The present work is a combination of these two approaches, and they are therefore outlined below.

The factors of soil formation are summarised by the seminal state factor equation

$$S, s = f(cl, o, r, p, t, \ldots)$$

where any soil S, or any soil property s, is a function of climate (cl), organisms (o), relief (r), parent material (p), time (t), and other factors such as aeolian deposition (Phillips, 1993). S, s are the dependent variables and the factors (cl, o, r, p, t, ...) are the independent variables. In theory, if the combination of factors that describe a soil system is known precisely, so are the soil properties – although the factors in the model define only the *state* of the soil, and do not describe the *processes* of pedogenesis (Birkeland, 1974).

Much has been written about this relationship, and it has been variously lauded, vigorously tested, and severely criticised (Birkeland, 1974; Amundson *et al.* 1994; Paton *et al.*, 1995; Thwaites and Schafer, 2000). Criticism, however, has not prevented it assuming paradigm-like status in itself. According to Hudson (1992), the state-factor equation fulfils two of Kuhn's (1970) requirements for a successful scientific paradigm: first, the apparent simplicity of the concept as a basis for pedological understanding with universal application attracted a large number of adherents; second, because it is a general statement implying that soils are distributed in a predictable way in response to systematic interactions of environmental factors, and lacks further specificity, it has stimulated much research.

Phillips (1999, p104), in responding to criticisms of the validity of the state-factor approach, claimed that the purpose and scope of the state-factor model is sometimes misunderstood: the factors are not intended to describe pedogenetic processes or soil components, they instead provide the context and boundary conditions within which soil genesis and evolution occur. Birkeland (1974) argued that the state-factor approach allows critical pedologic and geomorphic processes to be isolated and studied, whereas Thwaites and Schafer (2000) claimed that the model erroneously emphasises climatic and biological factors over more important topographical and lithological influences, and that modern pedogeomorphology (e.g. Roering *et al.*, in prep.) is more suited to modelling and understanding soil phenomena at a range of scales than is the state-factor model approach. However, Thwaites and Schafer (2000) themselves are perhaps underestimating the importance of the biological factor in the bioturbation effects of soil fauna and flora, as described by Paton *et al.* (1995) and Johnson (2000).

Pedogeomorphology attempts to describe and explain the relationships between soils and landforms, and investigates how landform (geomorphological) processes interact with soil-forming pedological processes (Gerard, 1993). In slope and catchment systems, the *catena* (Latin, = a chain) is a useful conceptual tool for understanding the relationships between slope morphometry and associated changes in soil morphological, chemical and physical properties. The catena concept was originally proposed as an aid to classifying and mapping grouped soils linked together by their topographic relationships (Milne, 1935), and the concept and its applications have since broadened and evolved to dominate much of modern pedogeomorpholocial research. As such, the catena concept has itself attained a kind of paradigm status and, as comprehensively described by Sommer and Schlicting (1997), catenary morphology and processes are increasingly being quantitatively modelled. For a detailed treatment of the development of the catena paradigm, and the state-of-the-art of catenary theory, the reader is referred to Sommer and Schlicting's (1997) review. For present purposes, it is noted that soils on catenary sequences are both genetically and ecologically linked because downslope soils depend on the solid phase/solute inputs from upslope soils, and that catenas can be classified according to how hydrological regimes influence solute translocation (Sommer and Schlicting, 1997). In addition Sommer and Schlicting (1997) emphasised that traditional pedogeomorphological approaches to understanding slope/catchment processes and evolution (*e.g.* Hall and Olson, 1991; Gerrard, 1993) focus on the solid phases of slope evolution, and as such are all constitute aspects of catenary research that need to be complemented by hydrological and geochemical studies. The soil-landscape paradigm affirms the importance of pedogeomorphological approaches to describing and modelling in a quantitative-mechanistic manner the relationships between slope and catchment systems and the soils they support.

The development of the soil-landscape paradigm reflects the success of using soil-landscape relationships to understand the spatial nature of soil phenomena. While the state-factor model has been important in the development of the paradigm, a pedogeomorphic emphasis is necessary for detailed mechanistic modelling and understanding of soil phenomena and landform, as exemplified by modern catenary research. The climate, organism and time variables of the state-factor approach provide the wider environmental context within which pedogeomorphological systems comprised of parent materials and relief play dominant roles in controlling soil-landscape systems. The collection of field data has been essential for the development of the soil-landscape paradigm, and will continue to be essential for future soil survey and pedological modelling.

1.2.3 The Need for Improved Soil Survey

The importance of understanding the distribution New Zealand's soil resources has been reflected in the extensive soil surveys performed throughout the last five decades. However, soil survey itself is now often regarded as expensive, time consuming and ultimately providing insufficiently precise information on soil variability to be practical in a management context. Standard soil surveys were not designed to provide the high-resolution (~ scale 1:6000) models and maps of the soil continuum required in detailed environmental modelling applications and site-specific crop management (Petersen, 1991). Thus there is a need for high-resolution soil data obtained in an efficient and cost effective manner.

Conventional soil survey methods use relationships between soil properties and more readily observed environmental features as a basis for mapping, and are derived from qualitative and complex mental models developed by the pedologist during field survey (McKenzie and Ryan, 1999). Unfortunately these mental models are rarely communicated and users of surveys find it difficult to separate evidence from interpretation (McKenzie and Ryan, 1999). Worse, soil survey has traditionally failed to communicate the methods by which results can be reproduced (Hewitt, 1993). In addition, models have traditionally not specified how much uncertainty they remove, and are susceptible to continual revision of predicted data so that they appear to fit better than the original predictive model (Cook *et al.*, 1996). This form of soil-landscape modelling used in conventional soil survey is therefore self-fulfilling. As such, soil survey as a science has been criticised for its reliance on the tacit knowledge of individual pedologists in developing soil maps, and its consequent lack of testability and verifiability through the scientific method. Therefore more objective and quantitative soil survey methods are needed to make soil survey a more reliable and repeatable scientific discipline, as well as providing soil data in a form more amenable to environmental modelling.

1.2.4 Modelling Soil Landscapes

The limitations of conventional soil survey presented above have been recognised for some time. An approach to soil survey that is considered more economical (with both time and money) and more quantitative and repeatable is soil-landscape modelling (Webb, 1994). Hewitt (1994) has defined soil-landscape modelling as the prediction of unobserved soil properties from observed landscape features. The objectives of soil-landscape modelling are, firstly, to provide the spatial information necessary for making land-use planning and management decisions, and secondly, to encapsulate an understanding of the spatial relationships in a landscape and their dynamics (Hewitt, 1994). The fundamental premise of soil-landscape modelling is that soils will vary in a systematic and predictable way according to where they lie in the landscape, as stated by the soil-landscape paradigm (Section 1.2.2). Importantly, the ability to predict soil types/properties from current landscape morphometry depends on the landscape and soils being in some form of dynamic equilibrium. These assumptions of predictable relationships and equilibrium encounter problems in landscapes that are actually adjusting to changed conditions, whether they be climatic, tectonic or anthropogenic. In these conditions a high degree of spatial and historical contingency exists.

Ultimately, a tested and verified soil-landscape model can be used to define a land system. A land system has been defined as an area, or group of areas, throughout which is a recurring pattern of topography, soils, and vegetation with a relatively uniform climate (Christian and Stewart, 1953). Another practical definition of a land system is the area of validity of a given soil-landscape model (Hewitt, 1994). Lynn and Basher (1994) have recommended that the land system approach be used in New Zealand with associated soil-landscape models to establish predictive models that give proportions and the distribution of types of terrain, the array of soils, and information on landscape history.

Traditional soil-landscape modelling and delineation of land systems are subject to the same criticisms levelled at conventional soil survey (Section 1.2.3): they depend on the tacit, subjective knowledge of individual pedologists, the methodology of their development is seldom made explicit, and they are not readily amenable to scientific repeatability and testing. The development of more quantitative methods of soil survey and soil-landscape modelling places pedology on a more scientific foundation, and lends greater credibility to the conventional means of conveying soil information – soil maps.

Maps are the most explicit representations of both soil survey data and soil-landscape models. As discussed by Burrough (1996), since most pedological phenomena are complex and vary with both space and time, soil scientists have been required to select the most important aspects of any given soil system and to use these as the basis for information storage and transfer, and in order to model natural phenomena in terms that are readily comprehensible it has been necessary to abstract and generalise information in the form of maps. Burrough (1996) has described two fundamental mapping systems: the *object model* and the *continuous field model.*

The *object model* is characterised by conventional chloropleth maps, where soil units are represented by discrete polygons (objects) separated from each other by infinitely sharp boundaries (Lagacherie *et al.*, 1996). Where the soil phenomenon under study is interpreted as a predominantly static, qualitatively complex entity that can be mapped on external features of the landscape the object model has been traditionally used, and properties within polygons are described by attributes whose values are assumed to be constant over the total extent of the object (Burrough, 1996). However, because of the implied homogeneity with map units, these conventional soil maps neither delineate all of an area's inherent variability nor represent specific soil attribute variation (Moore *et al.*, 1993). Two problems follow from this approach: (1) the lines drawn on the soil survey maps may not accurately depict the gradational nature of boundaries between map units and (2) the inferred inhomogeneities do not exist for many physical and chemical attributes that affect environmental modelling and soil-specific management (Moore *et al.*, 1993).

The *continuous field model* is used when single quantitative physical and chemical attributes are measured and mapped (Burrough, 1996), and presents obvious advantages over the object model in representing these important soil properties. Assumptions of homogeneity are unnecessary, and Digital Elevation Model and Geographic Information System technologies are particularly suited to representing continuous quantitative data with high spatial accuracy.

The present work is essentially a combination of the object model and continuous field model approaches. The quantitative SLMs presented here are an attempt to model and map soil series, conventionally represented by polygons, by using continuous digital terrain attributes. The mapping approach used here is therefore semicontinuous: soil classes, traditionally represented using the object model, are combined with continuous digital terrain data. The importance of Digital Elevation Model and Geographic Information System technologies to modern pedogeomorphological research is described in the next Section.

1.2.5 Quantitative Soil-Landscape Modelling Using Digital Elevation Models and Geographic Information Systems

Digital Elevation Models (DEMs) and Geographic Information Systems (GIS) have greatly enhanced soil-landscape modelling and delineation of land systems, and have great potential as research tools to; 1) enhance our understanding of the processes involved in the evolution of soil landscapes; 2) to enhance pedological research, and 3) to improve the quality and precision of the soil survey effort (Hammer *et al.*, 1991). Digital terrain analysis allows the generation of a suite of variables that reflect geomorphic, climatic and hydrologic processes (McKenzie and Ryan, 1999) that can be used to understand the nature and distribution of soil phenomena. Presented below is a review of the main theoretical underpinnings of quantitative soil-landscape modelling, including terrain analysis of landforms, applications of DEMs and GIS, the effects of DEM resolution, digital terrain attributes, and statistical/mathematical modelling techniques.

The importance of landform for understanding the spatial distribution of soil phenomena has long been recognised, and conventional stereoscopic terrain analysis has been an integral part in the planning and final mapping of soil surveys. Blaszczynski (1997) defined landforms as specific geomorphic features such as plains and mountain ranges to minor features such as individual hills and valleys. Belcher (1948, cited by Blaszczynski, 1997) stated that each individual landform represents separate and distinct soil characteristics, topography, rock materials, and groundwater conditions. The recurrence of landform, regardless of location, implies a recurrence of the basic characteristics of that landform (Belcher, 1948, cited by Blaszczynski, 1997). Lueder (1959, cited by Blaszczynski, 1997) described the landform unit as a terrain feature or terrain habitat, usually of the third order (hills and valleys), created by natural processes in such a way that it may be described and recognised in terms of typical features wherever it may occur. When identified, the landform unit provides dependable information concerning its own structure, composition and uniformity (Lueder, 1959, cited by Blaszczynski, 1997).

The ability to analyse and quantify the morphology of the surface of the earth in terms of landform characteristics is essential for understanding of the physical, chemical and biological processes that occur within the landscape (Blaszczynski, 1997). Digital terrain analysis using DEMs and GIS provides an efficient method of quantitative landform characterisation that surpasses time-consuming and relatively subjective stereoscopic analysis, and the use of DEM-derived terrain attributes promises increased ability to model and understand soil-landscape relationships.

Hammer *et al.* (1991) noted that GIS potentially offer great promise to expand the quantitative databases of pedology and geomorphology, and that the potential exists to weld together these related sciences through three-dimensional analysis and displays in ways not previously possible. The spatial analysis capabilities of GIS and their capacity for cartographic database layering offer an ideal method to incorporate soil survey data into management plans (Hammer *et al.*, 1991). Moore *et al.* (1993) have emphasised the ability of GIS to organise and build on existing land resource data sets, as well as improve our knowledge of environmental processes and promote economical and sustainable land management.

Several important papers have established the validity of using quantitative soil-landscape models to predict soil classes and attributes (see Moore *et al.*, 1993; McKenzie and Austin, 1993; Gessler *et al.*, 1995; Hammer *et al.*, 1995; Cook *et al.*, 1996; Townsend and Walsh, 1996; McKenzie and Ryan, 1999; Mendonca Santos *et al.*, 2000, Park and Burt, 2002). In New Zealand, terrain analysis based on DEMs and GIS has already been used to some extent. Dymond and Luckman (1994) investigated whether or not a relationship between soil class and DEM-derived attributes exists within an existing soil survey of the Port Hills, Canterbury. They concluded that it was possible to construct a soil/DEM model for the Port Hills that can be used to predict a group of soil series from DEM attributes alone (Dymond and Luckman, 1994). Dymond *et al.* (1995) developed an algorithm for automating the mapping of land components from digital elevation data. The land components mapped in this way give a complete polygonisation of a hilly landscape and are a reasonable approximation of manually mapped land components using stereo photo interpretation, a slow and labour intensive method (Dymond *et al.*, 1995). Bakker *et al.* (1996) automatically classified the valley forms on the Mamuku Plateau using a DEM, and concluded that DEMs are useful in landscape analysis especially if combined with traditional geomorphologic analysis including aerial photograph interpretation. Jones (1998), in a study of the soils of the Woodlaw Forest in Southland, developed a soil landscape model that was a set of predictive relationships between observable landscape features and soil classes. For this study GIS were found to be very useful tools for soil-landscape modelling, for the spatial analysis of soil properties and for the effective presentation of soil information (Jones, 1998).

DEMs can be used to calculate geomorphologic variables such as elevation, slope, aspect, slope plan curvature, slope profile curvature, and a range of other characteristics to stratify the landscape under study into quantitatively defined landform components such as interfluves (ridges), sideslopes, footslopes, noses and hollows. In combination with climate data (precipitation, temperature, solar radiation and other spatial data on variation of state factors), this landscape information can be used to predict which soil classes and properties will be present in particular locations. A sampling strategy can then be designed to test the inferred soil-landscape relationships (Hewitt, 1994).

A DEM is a quantitative representation of the continuous surface of the ground by a large number of selected points, with known *xyz* coordinates in an arbitrary coordinate field. Although DEMs were introduced in the late 1950s (see Miller and Laflamme, 1958), their application potential was not fully realised until the late 1980s when DEMs became widely available (Wang and Yin, 1998). With the advent of GIS, DEMs have been used to delineate drainage networks and watershed boundaries, and to calculate slope characteristics (Wang and Yin, 1998). Topography defines the effects of gravity on the movement of water and sediments in a catchment, and therefore DEMs play a considerable role in hydrologic simulation, and soil erosion and landscape-evolution simulation (Zhang *et al.*, 1999).

Most DEMs are derived from digitised contour information or spot heights from topographic maps, and contour intervals of 20 m or more are standard (Pickup and Marks, 2000). Contours, spot heights and stream lines can either be hand digitised, scanned from paper maps, or digital source data can be obtained from various mapping agencies (Gallant *et al.*, 1996). DEMs have also been constructed using high-resolution Global Positioning System (GPS) surveys (Brasington *et al.*, 2000) and combined radar altimetry/differential GPS data collected during geophysical surveys (Pickup and Marks, 2000). Increasingly, laser altimetry is being used to produce high-resolution elevation data.

Unlike paper maps, DEMs do not have an intrinsic scale, but they do have a resolution (Gallant *et al.*, 1996). Various studies over the past decade have investigated the effects of DEM resolution on the calculation of slopes and associated hydrological modelling processes. Many authors have noted the inconsistency of different algorithms and interpolation techniques in calculating slopes from DEMs, and have noted inconsistencies within the same DEM for different terrain complexity. Zhang *et al.* (1999) pointed out that this may be due to the inherent geometry of the landscape, and note that a number of authors have demonstrated that the topography of the earth generally exhibits fractal characteristics. This fact implies that there should be a linkage between the observed topography and the scale of the observation. Given that slope is the derivative of the local topography, its measurement should therefore also be a function of scale. If so, this linkage may explain some of the difficulties of the measurement of slopes from DEMs. Fractal techniques are therefore potentially useful in providing better estimates of the local slope using only coarse resolution data (Zhang *et al.*, 1999).

Pickup and Marks (2000) have researched the effect of the real land surface on the construction of DEMs. While reasonably good information is sometimes available for the steeper parts of the landscape, areas with gentle slopes, such as floodplains, are poorly described. In addition, when contour information is sparse, DEM generation involves interpolation across many grid cells and can produce artefacts that distort slopes and flowpaths, and may result in highly inaccurate drainage networks. Pickup and Marks (2000), using experiments on floodplain areas of central Australia, showed that DEMs derived from radar altimetry data obtained in the course of airborne gamma radiometric studies provided a better reproduction of patterns of water flow and flooding than DEMs based on 20 m contour data from 1:100,000 topographic maps. A comparison of mapped drainage lines with those generated from DEMs based on radar altimetry data also yielded good results for flat areas, but declined in accuracy in more rugged terrain where the flight line spacing was too great to capture all topographic variations. In the latter case, contour data were found to be superior (Pickup and Marks, 2000).

Zhang *et al.* (1999) have investigated the variation in slopes derived from DEMs of varying scales. Three factors were found which complicate the effective application of DEMs for calculating slopes in the context of runoff and soil-erosion modelling:

- Different results are obtained by different methods of calculating slope and aspect.

- Coarser-resolution DEMs such as those at regional, continental and global scales are more commonly defined by a latitude/longitude projection, where pixel size varies with distance from the equator influencing the accuracy of slope estimates, especially in high latitude areas.

- Slopes derived from DEMs vary with spatial resolution, becoming lower at larger pixel sizes. High slope values are produced when using high resolution DEMs but slopes are underestimated when using the coarse resolution DEMs. This underestimation can seriously affect the accuracy of hydrological and geomorphological models implemented at coarse resolutions (Zhang *et al.*, 1999).

Schoorl *et al.* (2000), in a study investigating the effect of DEM resolution on three-dimensional landscape process modelling, found that with coarser DEM resolution the models overpredicted erosion and underpredicted resedimentation. Garbrecht and Martz (1994) found that there was a DEM grid size dependency on the minimum source channel length in hydrological studies. In general, the grid size dependency was introduced by the inability of a DEM to accurately reproduce drainage features that were at the same scale as the spatial resolution of the DEM. For sinuous channels, this resulted in shorter channel lengths, and for networks with high drainage density it led to channel and drainage area capturing. Channel and drainage area capturing occurs when the DEM grid can no longer resolve the separation between channels or drainage boundaries (Garbrecht and Martz, 1994). Zhang and Montgomery (1994) investigated the effect of DEM resolution on the distribution of derived slopes and found that slope angle consistently decreased with increasing grid size. Wang and Yin (1998) found that DEM resolution could have a profound effect of the calculation of slope and the modelling of related hydrological and geomorphological processes. They determined that two major factors affect the accuracy of stream networks: DEM resolution and drainage density.

A choice of appropriate DEM resolution must be guided by knowledge of the processes or patterns being studied (Gallant *et al.*, 1996). Surface hydrology and erosion studies are probably the most demanding of high quality topographic data, and require resolutions of 10 metres or better to adequately represent the processes (Zhang and Montgomery, 1994). Gessler (1996) has shown there is a considerable loss of capacity to predict soil characteristics from terrain as cell size becomes greater than 80 metres. Indeed, much of the local variability in both terrain characteristics and soil properties requires a grid cell spacing of 10 m or less to be captured fully (Gessler, 1996). Pickup and Marks (2000) found that a DEM grid cell size of 100 metres interpolated from radar altimetry data was a reasonable compromise between the loss of information on terrain characteristics because of the smoothing associated with larger grid cells, and the generation of artefacts by the interpolation routines used in DEM generation as grid cells become smaller. Hutchinson and Gallant (2000) outlined a method for determining optimum DEM resolution that monitored root mean square slope as a function of DEM grid cell size. They found that a 15 m resolution was optimum and most faithfully honoured the contour data from which the DEMs were derived.

As shown by the research reviewed above, the search for an optimum DEM resolution is an ongoing, unsolved problem. Not only does minimum DEM cell size depend on the resolution of the base data from which it is derived, it is also dependent of the character of the terrain itself. As such it appears that optimum DEM resolution must be determined in the context of the inherent scale of the terrain and the phenomena to be modelled. In New Zealand most DEMs are derived from 1:50,000-scale 20 m contour topographic maps, and a range of resolutions are available (*e.g.* 50 m, 20 m and 10 m). For the present work, the highest-resolution DEM available for the study area (25 m) was used in the development of quantitative SLMs.

1.2.6 Digital Terrain Attributes

Terrain attributes are descriptors of landscape elements calculated from DEMs, and have been used in a wide range of hydrological, geomorphological and ecological research (Wilson and Gallant, 2000a). The present discussion will focus on primary and secondary digital terrain attributes used in the development of qSLM 1 and qSLM 2. These terrain attributes, their definitions and significance are summarised in Table 1.2.

Primary terrain attributes (Table 1.2) include slope, aspect, profile and plan curvature and upslope area, and most of these are calculated from the directional derivatives of a topographic surface – the DEM (Wilson and Gallant, 2000b; see Appendix 1). Slope, the most widely used topographic measurement, influences flow rates of water and sediment by controlling the rate of energy expenditure or stream power available to drive the flow. Aspect defines the slope direction and therefore the direction of flow. Knowledge of how aspect varies throughout a catchment provides the information necessary to determine what upslope land area contributes to the flow at any point in the catchment (Zevenbergen and Thorne, 1987). Another important primary terrain attribute is curvature, which is generally understood as a directional property (Blaszczynski, 1997). Profile curvature, the rate of change of slope, affects flow acceleration and deceleration and therefore influences aggradation and degradation (Zevenbergen and Thorne, 1987). Plan curvature, the curvature of the land surface transverse to the slope direction, influences flow convergence and divergence (Zevenbergen and Thorne, 1987). Upslope area, otherwise known as specific catchment area, is conventionally defined as contributing area per unit contour length (Tarboton, 2000). When using DEMs in terrain analysis, upslope area is defined as contributing area per unit grid cell size (Tarboton, 2000), and is useful for quantifying runoff volume, steady-state runoff rate, soil characteristics and soil-water content (Wilson and Gallant, 2000b).

Table 1.2

Definitions and significance of primary and secondary terrain attributes derived from DEM data and used in the present work. After McSweeney *et al.* (1994) and Wilson and Gallant (2000b).

	Attribute	Definition	Significance
Primary Terrain Attributes	Altitude	Elevation	Climate, vegetation, potential energy
	Aspect	Slope azimuth	Insolation, evapotranspiration, flora & fauna distribution & abundance
	Slope (β)	Gradient	Overland & subsurface flow velocity & runoff rate, precipitation, vegetation, geomorphology, soil water content, land capability class
	Profile Curvature	Slope profile curvature	Flow acceleration, erosion/deposition rate, geomorphology
	Plan Curvature	Contour curvature	Converging/diverging flow, soil water content, soil characteristics
	Upslope Area (A_s)	Catchment area above a short length of contour or DEM grid cell	Runoff volume, steady-state runoff rate, soil characteristics, soil-water content, geomorphology
Secondary Terrain Attributes	Wetness Index	$WI = \ln\left(\frac{A_s}{\tan\beta}\right)$	Predicts zones of saturation where A_s is large & where β is small, usually along drainage paths & in zones of water concentration in landscapes
	Stream Power Index	$SPI = \ln\left(A_s \tan\beta\right)$	Measure of erosive power of flowing water based on the assumption that discharge is proportional to A_s. Predicts net erosion in areas of profile convexity & net deposition in areas of profile concavity

Secondary terrain attributes (Table 1.2) are computed from two or more primary attributes, and are important because they can describe pattern as a function of process (Wilson and Gallant, 2000b). The two secondary terrain attributes discussed here, and used in the present work, are the Wetness and Stream Power Indices.

The Wetness Index (WI), also known as the sediment transport index (Moore *et al.*, 1993), the steady-state wetness index (Gessler *et al.*, 1995) and the compound topographic index (McKenzie and Ryan, 1999) has proven to be an important secondary terrain attribute for soil-landscape studies. Local landform has a major impact on soils by controlling water and sediment movement, and the WI is a useful integrative topographic variable that is a guide to water and sediment movement in particular landscapes (McKenzie and Ryan, 1999). The WI quantifies the relative saturation of positions in the landscape and has proven useful for predicting soil properties (McKenzie and Ryan, 1999). The WI is calculated as

$$WI = \ln\left(\frac{A_s}{\tan\beta}\right)$$

where A_s is the specific contributing area and β is slope angle. The form of the equation reflects the physical relationship between catchment area of a particular point in the landscape (influenced by A_s) and the slope angle (β) of that point. The WI predicts zones of saturation where A_s is large and where β is small, usually along drainage paths and in zones of water concentration in landscapes. This equation applies to equilibrium conditions and when soil depth and hydraulic conductivity are assumed to be uniform. Aggregated over a broad (i.e. non-hillslope) region, the assumption of uniform soils in broad-scale topographic modelling is not necessarily unreasonable (Townsend and Walsh, 1996).

The WI has been very successful in predicting soil attributes (e.g. Moore *et al.*, 1993; Gessler *et al.*, 1995; McKenzie and Ryan, 1999), although the assumption of soil uniformity led to underprediction or overprediction of wetness potential in areas with variable soils in one study (Townsend and Walsh, 1996). Because the WI is ultimately derived from slope data, which are dependent on DEM resolution, the WI can change according to grid cell size.

The Stream Power Index (SPI) is a measure of the erosive capacity of water flowing through a point in the landscape. The SPI is calculated as

$$SPI = \ln\left(A_s \tan\beta\right)$$

where A_s is the specific contributing area and β is slope angle. As with the WI, the form of the SPI equation reflects the physical relationship between amounts of water delivered to a particular point in the landscape (influenced by A_s) and the slope angle (β) of that point. The SPI is based on the assumption that discharge is proportional to A_s, and predicts that the erosive capacity of water will be greatest where A_s and β are large. The SPI also predicts net erosion in areas of profile convexity and net deposition in areas of profile concavity (Wilson and Gallant, 2000b). The SPI has been a useful predictor variable for both hydrological and pedogeomorphological studies (Moore *et al.*, 1988).

The primary and secondary terrain attributes discussed here are used in the present work for quantitative soil-landscape modelling. A more detailed discussion of their generation is presented in Chapter 3.

1.2.7 Quantitative Tools in Soil-Landscape Modelling

The development of quantitative SLMs is dependent on the application of mathematical tools in order to establish relationships between soil types/properties and landscape features/terrain attributes. Most of the quantitative SLMs that have been developed in the last decade are statistical in nature. McKenzie and Austin (1993), Moore *et al.* (1993) and Gessler *et al.* (1995) used multiple linear regression to identify significant correlations between soil properties and a range of soil and terrain attributes, and Gessler *et al.* (1996) used simple linear models to establish relationships between total carbon and WI. Other methods include the use of regression (probability) trees (McKenzie and Ryan, 1999) that have the advantages of simply modelling nonlinear relationships using both continuous and nominal explanatory and response variables. Alternative approaches have utilised conditional probabilities to produce predictive maps of soil classes and properties (Lagacherie and Voltz, 2000), fuzzy classification procedures to identify SLUs (Irvin *et al.*, 1997) and artificial intelligence/expert systems to map organic matter (Cook *et al.*, 1996).

Most of these studies have concentrated primarily on the spatial modelling of quantitative measurements of soil physical and chemical properties. For the present work, the spatial modelling of nominal/categorical data was the main focus. These data were comprised of pre-existing soil mapping units (SMUs) from the soil map of Wilson (1970) and spatially referenced soil taxonomic units (STUs) obtained in the field for this study. Discriminant Function Analysis was the statistical technique used to identify relationships between SMU/STU data and digital terrain attributes.

The general theory of Discriminant Function Analysis (DFA) is discussed in detail elsewhere (see Webster and Oliver, 1990; Manly, 1994; Hair *et al.*, 1998), and a brief review is presented here. DFA is a multivariate statistical technique that involves deriving a variate (a linear combination of variables with empirically determined weights) of two or more independent variables that will discriminate best between *a priori* defined groups of categorical data. DFA identifies the variables with the greatest differences between groups and derives a discriminant coefficient that weights each variable to reflect these differences and maximise separation between groups. In the context of the present analysis the *a priori* defined groups of categorical data were the randomised samples of soil series-based SMUs/STUs at specific DEM grid cell locations, and the independent variables were the digital terrain attributes.

DFA was used to test the hypothesis that the group means of digital terrain attributes for at least three *a priori* defined SMU/STU groups were equal *i.e.*

$$H_0: x_1 = x_2 = x_3$$

$$H_1: x_1 \neq x_2 \neq x_3$$

Since there were at least three *a priori* defined SMU groups on each lithological unit, multiple *dimensions* of discrimination were constructed using discriminant functions.

The discriminant functions are of the form

$$Z_{jk} = a + W_1X_{1k} + W_2X_{2k} + \ldots + W_nX_{nk}$$

where Z_{jk} = discriminant Z score of discriminant function j corresponding to a SMU/STU for observation k, a = intercept, W_i = discriminant coefficient (weight) for independent variable i, and X_{ik} = independent variable i for observation k. The discriminant functions are used to generate discriminant function scores by a linear combination of terrain attribute predictor variables. For a given DEM grid cell, the SMU/STU corresponding to the discriminant function that produces the highest score is the most probable one to occur at that location. In selecting the highest discriminant function scores in a GIS, a predictive soil map can be constructed (Chapters 4 and 5).

1.2.8 Summary

The present work is concerned with soil-landscape modelling in North Otago, and uses a quantitative-functional approach. The theoretical context of this work can be summarised as follows:

- While soils can be considered an archetype of a complex dynamic Earth Surface System, order exists at certain scales that is amenable to scientific modelling.

- Scientific understanding of soil landscapes is encapsulated by the soil-landscape paradigm, which is the legacy of both the state-factor and pedogeomorphological approaches to understanding soil phenomena.

- Traditional approaches to modelling soil landscapes using the soil-landscape paradigm have depended on conventional soil survey and depiction of soil data on chloropleth maps, which have been criticised as being unscientific and unrealistic, respectively.

- DEM and GIS technologies can be used to model soil landscapes in a more scientific and realistic manner by using quantitatively defined terrain attributes as predictor variables for soil types and properties.

Therefore, GIS and DEM technologies have been applied to the problem of producing quantitative SLMs of North Otago. The aim and objectives of this work are stated below.

1.3 Aim and Objectives for the Study

High-resolution soil data are necessary for sound management of soil resources and for understanding the fundamental composition of soil landscapes. The soils of North Otago have already been mapped at scale 1:50,000 (Wilson, 1970; Sections 2.7 and 3.1), but these soil data suffer from the problems associated with conventional soil survey, with their dependence on qualitative conceptual models that are not amenable to scientific validation. With the advent of DEM and GIS technologies it is possible to develop quantitatively defined models of soil landscapes that are able to validated or refuted by future researchers. Importantly, these technologies enable soil-landscape models to be automatically extrapolated to other areas, making the construction of rigorously defined models covering large areas a feasible prospect. Therefore the aim of the present work was to develop quantitative SLMs for North Otago. To achieve this, three objectives were defined:

- To develop a quantitative SLM to replicate the mapping rules used for the 1:50,000-scale soil map of Wilson (1970). This was to see if Wilson's (1970) conceptual models could be captured in a quantitative manner in order to automatically produce soil maps of unmapped areas.

- To develop an independent quantitative SLM based on a new soil data set derived from a randomised-stratified sample of soil profiles observed from auger borings.

- To investigate relationships between A horizon percent carbon/nitrogen and soil taxa, parent materials, digital terrain attributes and microclimate data.

The goal of this study is to produce digital soil maps that can ultimately be integrated into the wider GrowOtago project, and used in combination with digital microclimate data to assist in land management decision-making. These objectives are addressed in Chapters 4, 5 and 6, respectively.

Chapter 2

The Study Area

2.1 Location

The study area is located in coastal North Otago in the South Island of New Zealand (Figure 2.1), and covers approximately 20,000 ha of the North Otago downlands and downlands margin to the south of the Waitaki River. The nearest significant population centre is Oamaru, approximately 5 km to the south-east of the eastern margin of the study area.

The Waitaki District in North Otago is a sparsely populated (~20,000 people) area of farmland and horticultural enterprises. In addition to these primary industries Oamaru has a growing tourism industry dealing in wildlife (penguins) and natural history (fossil trail).

The Otago Regional Council has recently introduced a project to stimulate rural economic growth, using high-resolution soil and microclimate data to identify new opportunities to improve production and assist in management decisions involving agricultural and horticultural production. The study area outlined above will be incorporated into a wider model of soil and microclimatic distribution in the North Otago region.

2.2 Climate

Kirkpatrick (1999) has divided the region into distinct climate districts, each characterised by a specific range of temperatures and precipitation (Figure 2.2). The study area is situated within Climate District 1, which is characterised by low annual rainfalls of 500-800 mm and slightly more precipitation in the summer months than in other seasons. Typically, northeasterly winds prevail in coastal areas whereas north-westerlies are more frequent inland. Summers in these areas are warm and winters are cool with frost and occasional snow. Mean annual temperatures for the study area range from 10-11 °C.

NIWA (2001) has produced preliminary maps (1:50,000 scale) of climatic variables of interest to those land users involved in agricultural and horticultural production in North Otago. Figures 2.3 and 2.4 show the summer (January-March) mean air temperature and five-year lowest summer (January-March) rainfall, respectively. The study area lies within the warmest areas of the North Otago downlands (Figure 2.3) although the highest elevations in the study area are slightly cooler than the valleys, reflecting their more exposed nature. Preliminary wind speed data are shown in Figure 2.22 (Section 2.5).

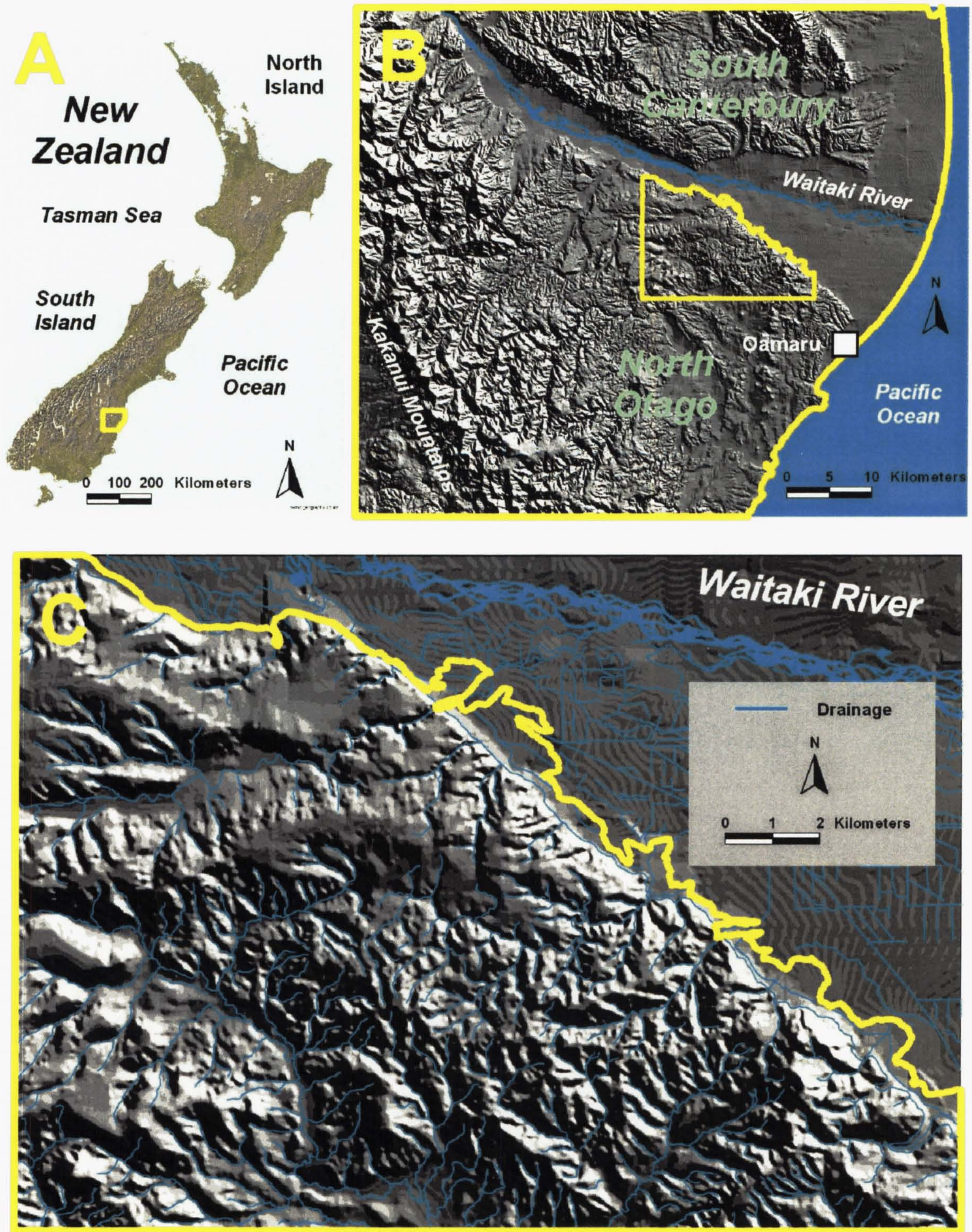


Figure 2.1

A) Location of North Otago in South Island, New Zealand.

B) Location of the study area in North Otago.

C) Detail of the study area.

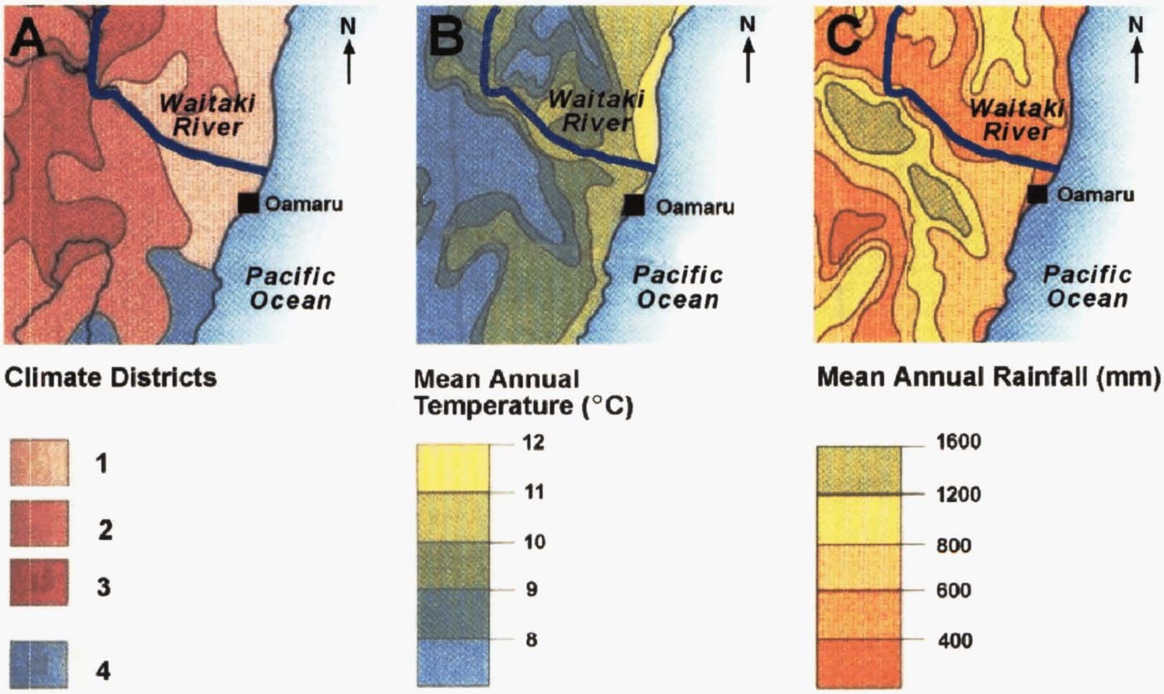


Figure 2.2

A) Climate districts of North Otago and South Canterbury.
1 = low annual rainfalls of 500-800 mm with slightly more in summer than in other seasons, warm summers with hot north-westerlies and cool winters with frost and occasional snow, north-easterlies prevail with north-westerlies more frequent inland. 2 = cooler and wetter than 1 with rainfall 800-1500 mm, north-westerlies predominate, snow may lie for weeks in winter. 3 = semi-arid areas with annual rainfall 300-500 mm, very hot summers and cold winters. 4 = warm summers and cool winters, rainfall 500-900 mm evenly distributed but slight winter minimum.

B) Mean annual temperature (°C) of North Otago and South Canterbury.

C) Mean annual rainfall (mm) of North Otago and South Canterbury.

Adapted from Kirkpatrick (1999).

The effect of winter precipitation on soil moisture content in the North Otago downlands is evident in the true-colour satellite image time series shown in Figure 2.5. From June 5 to June 10 2001 there was an increase in snow cover (white) on the Kakanui Mountains, which decreased to some extent by August 15. Over the same period an expansion of green (photosynthesising) vegetation is apparent on both the downlands and the Waitaki River floodplain. Despite the cool winter temperatures this was a period of high pasture growth, although the true optimum is in spring.

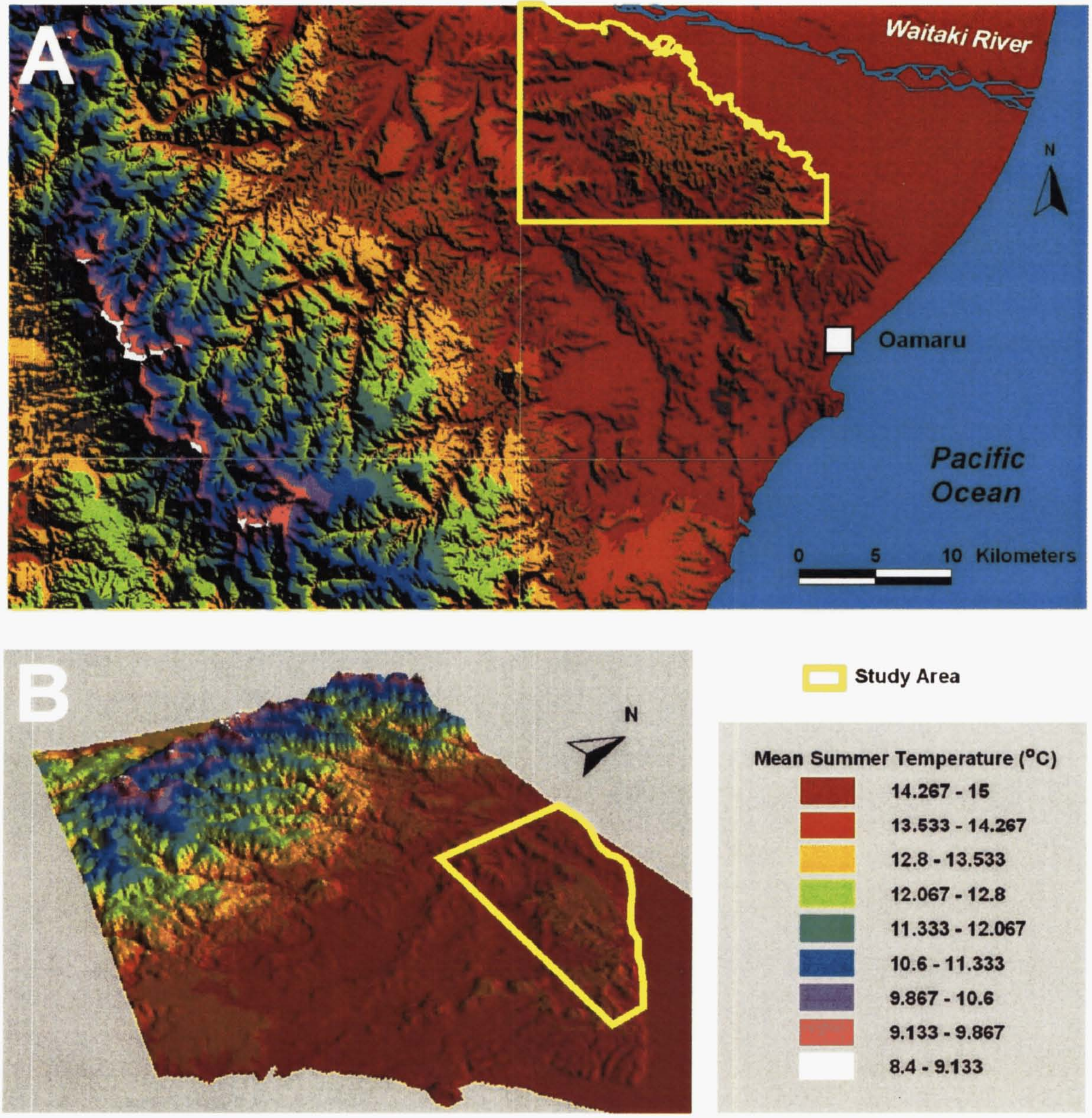


Figure 2.3

A) Summer (January-March) mean air temperature (°C) of North Otago, overlain by a shaded digital relief model illuminated from the north-east. The study area is indicated.

B) 3D perspective of the summer mean air temperature of North Otago, looking north-west up the lower Waitaki Valley. The study area is indicated. Note the decrease in temperature with increasing elevation.

Climate data from NIWA (2001).

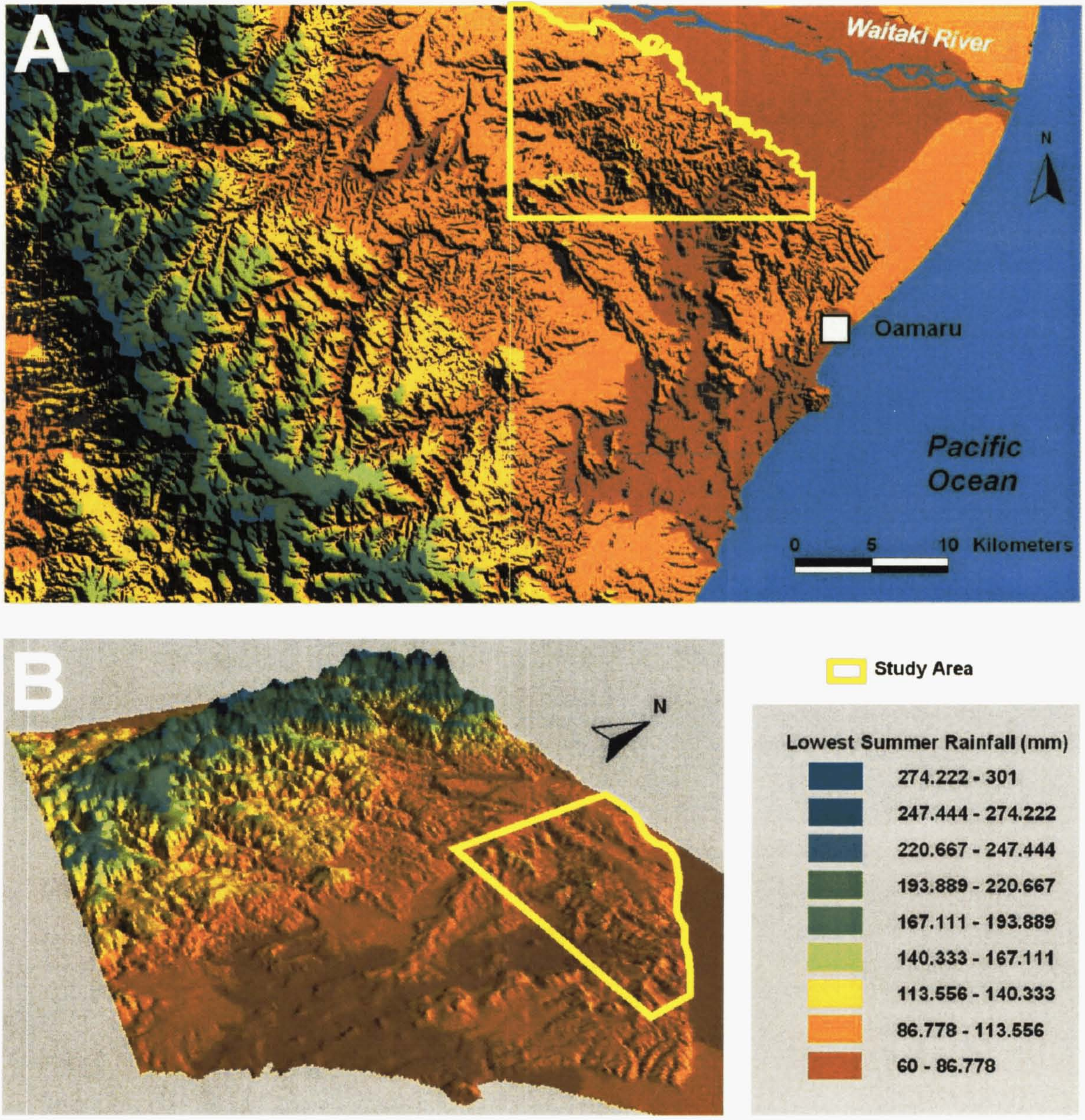


Figure 2.4

A) Lowest summer (January-March) rainfall in 1 out of every 5 years (mm) of North Otago, overlain by a shaded digital relief model illuminated from the north-east. The study area is indicated.

B) 3D perspective of the lowest summer rainfall (mm) of North Otago, looking north-west up the lower Waitaki Valley. The study area is indicated. Note the increase in rainfall with increasing elevation.

Climate data from NIWA (2001).

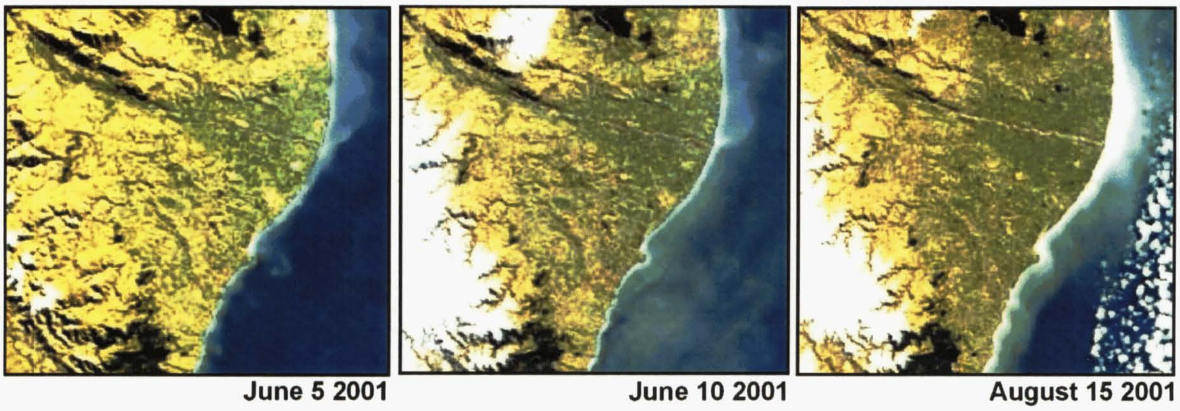


Figure 2.5

Satellite images of North Otago and South Canterbury captured in June and August 2001, during the time of field work for this study. From June 5 to June 10 there is an increase in snow cover on the Kakanui Mountains (white), which then reduces in extent by August 15. From June 5 to August 15 there is an increase in green vegetation cover on the North Otago downlands and Waitaki River floodplain due to increasing soil moisture content over winter.

These true-colour images were captured by the MODIS sensor on the Terra satellite. From *http://www.visibleearth.nasa.gov*. Contrast and brightness have been modified.

2.3 Land Use

Land use within the study area is dominantly agricultural (see Figure 2.6, from Bradley, 2000). Much of the area is devoted to dryland sheep and beef farming, with a small but significant number of properties also farming deer. However, conversion to dairying has been occurring for some time on the Waitaki River floodplain immediately to the north of the study area, which is readily amenable to irrigation sourced from the Waitaki River. More recently, properties within the study area itself are converting from traditional sheep and beef enterprises to dairy farms. This entails pumping water from the Waitaki River floodplain up onto the high terraces adjacent to the downlands margin and installing extensive irrigation systems – a significant investment. More extensive irrigation schemes have been proposed that would pump water onto the terraces, then gravity feed it into the valleys further south of the river. If these schemes go ahead, it is likely dairy conversion will expand.

Outside of the study area, nearer to Oamaru, a large area of Vertic Melanic Soils supports intensive market gardening. Within the study area horticultural production is generally limited to mixed cropping on a few properties, particularly in areas with Tokarahi Soils (see Appendix 2). Some landowners on the downlands margin to the south of the Waitaki River, whose properties have a northern aspect, are considering diversifying into viticulture. Wider research into microclimate mapping (see Section 2.2, and Figures 2.3

and 2.4) and soil resource inventory (of which the present work is a part) will provide resource data for land use diversification to make the most of the horticultural potential of the region.

Figure 2.6

Satellite image of North Otago. Note how the regular grid pattern of fields on the Waitaki River alluvial plain gives way to a more convoluted pattern dictated by the topography of the downlands. Green indicated pasture, brown indicates bare soil/recent cultivation.

From Bradley (2000).

2.4 Geology

The geological parent materials of North Otago are a regional manifestation of the wider syn-rift, passive margin and active margin episodes that have influenced the tectonic development of the New Zealand sub-continent (King *et al.*, 1999). The sequence is comprised of Palaeozoic metamorphic rocks overlain by a succession of marine transgressive/regressive Tertiary to recent non-marine and marine sediments interrupted with volcanic deposits. Figure 2.7 shows the evolution of the Great South Basin, the depositional environment in which the sedimentary and igneous lithologies of North Otago developed from the Latest Cretaceous to the Earliest Pliocene.

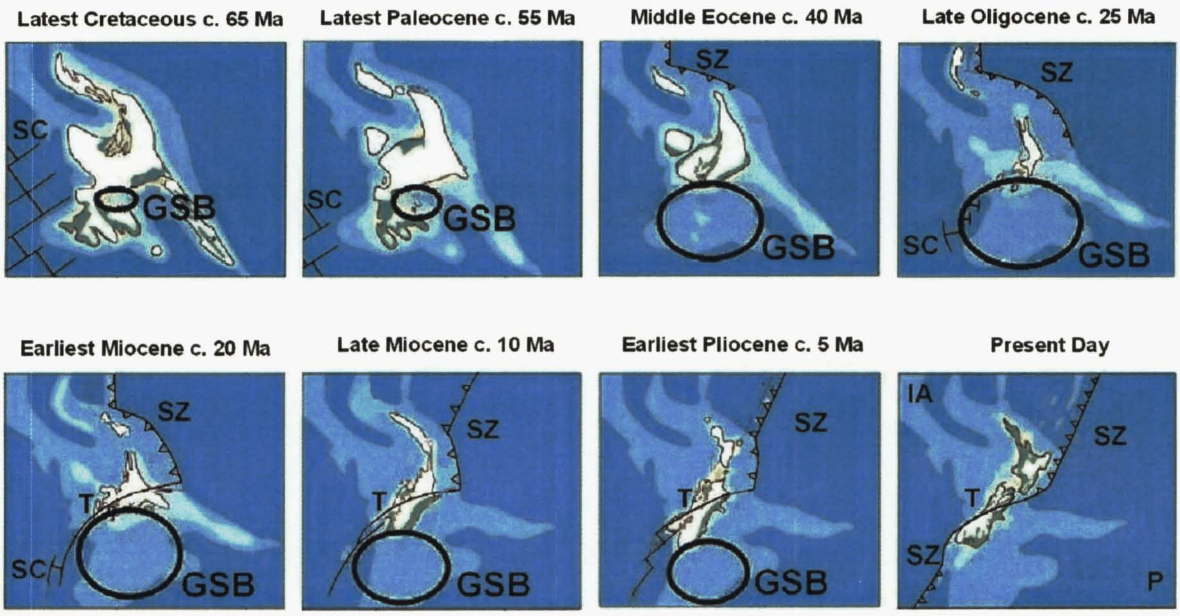


Figure 2.7

Position of the Great South Basin (GSB), the depositional environment in which the sedimentary and igneous lithologies of North Otago developed, from the Latest Cretaceous to the Earliest Pliocene (Ma = millions of years ago), and the present-day Indo-Australian (IA) and Pacific (P) plate boundary configuration.

SC = Spreading Centre; SZ = Subduction Zone; T = Transform Plate Boundary.

Colour coding: black outline = paleocoastline; white = terrestrial non-deposition; green = terrestrial deposition; yellow = marginal marine sand-dominated facies; pale blue = continental shelf; mid-blue = continental slope; dark blue = deep ocean.

Adapted from *http://www.gns.cri.nz/earthhist/nz_origins/paleo/index.html*.

The most up-to-date regional geological information for North Otago is provided by a 1:250,000 QMAP geological database that includes digital spatial information, map unit descriptions and age data (Forsyth, 2001). Mapping units are chronostratigraphic. The data presented in Figure 2.8, adapted from the Waitaki QMAP GIS database, emphasise age and lithological composition, and all Quaternary materials have been amalgamated into one map unit. The Group and Formation nomenclature of Forsyth (2001) have not been included so as to avoid confusion with the nomenclature originally used by Gage (1957, see Figure 2.10), and retained here. The following discussion of the regional geological and tectonic setting of North Otago is from Forsyth (2001).

The basement rocks of North Otago are part of the Rakaia tectonostratigraphic terrane, a subcomponent of the wider Torlesse composite terrane of eastern New Zealand. These rocks are composed of pumpellyite-actinolite metamorphic facies, and display two major mineral and textural zones reflecting low-grade metamorphism. The basement rocks exposed in the North Otago downlands, and some areas within the Kakanui Mountains, retain their primary appearance and sedimentary structure. These rocks contain metamorphic minerals that impart a weak cleavage to sandstones and a slaty cleavage to mudstones. The remaining areas within the Kakanui Mountains are composed of a more metamorphosed textural zone of well-foliated rocks, some containing primary sedimentary structures. Mudstones are metamorphosed to phyllites, and sandstone to meta-sandstone. The rocks in both textural zones are termed semischist.

The Rakaia Terrane rocks are interpreted to have been deposited in a huge submarine fan complex during the Late Carboniferous on an actively subducting ocean floor at the Pacific margin of Gondwanaland, which was subsequently altered by regional metamorphism throughout the Jurassic. Uplift and exhumation of these metamorphic rocks occurred in the Cretaceous, to produce the landscape adjacent to the Great South Basin shown in the first panel of Figure 2.7.

Regional subsidence of the New Zealand subcontinent in the Paleocene produced non-marine quartzose sandstone and mudstone (including coal measures) that overlie the semischist of the Rakaia Terrain. Eocene marine-transgressive sediments buried these non-marine deposits (see Figure 2.8), with submarine volcanic activity also occurring at this time, and also in the Oligocene. A regional paraconformity exists in the mid-Oligocene, representing a period of submarine erosion or non-deposition, and separates the underlying Oligocene volcanics and intrusives from overlying Oligocene greensands and limestones. These rocks were deposited in a wide range of shallow marine environments ranging from shoreface to outer shelf and offshore bars. The change in lithologies reflects changes in sediment provenance, which was determined by the wider evolution of the region (see Figure 2.7).

Late Miocene regional tectonic uplift resulted in marine regression which produced non-marine schist and greywacke conglomerate and lacustrine sediments. At this time the Miocene Dunedin Volcanic Group was also formed by basaltic lava flows and tuff rings. Pliocene gravels cemented with clay and iron oxides unconformably overlie these and are in turn unconformably overlain by a range of Quaternary alluvial fan, terrace, floodplain, beach and estuarine deposits. Older gravel deposits are preserved on the higher elevations of the North Otago downlands. A mantle of loess covers much of the North Otago region (see Section 2.5.2).

A comprehensive synoptic geological history of North Otago after Gage (1957) is presented in Table 2.1. The lithological units mapped by Gage (1957) within the study area are indicated in bold italics, and are further discussed in the context of geological soil parent materials in Section 2.5.1.

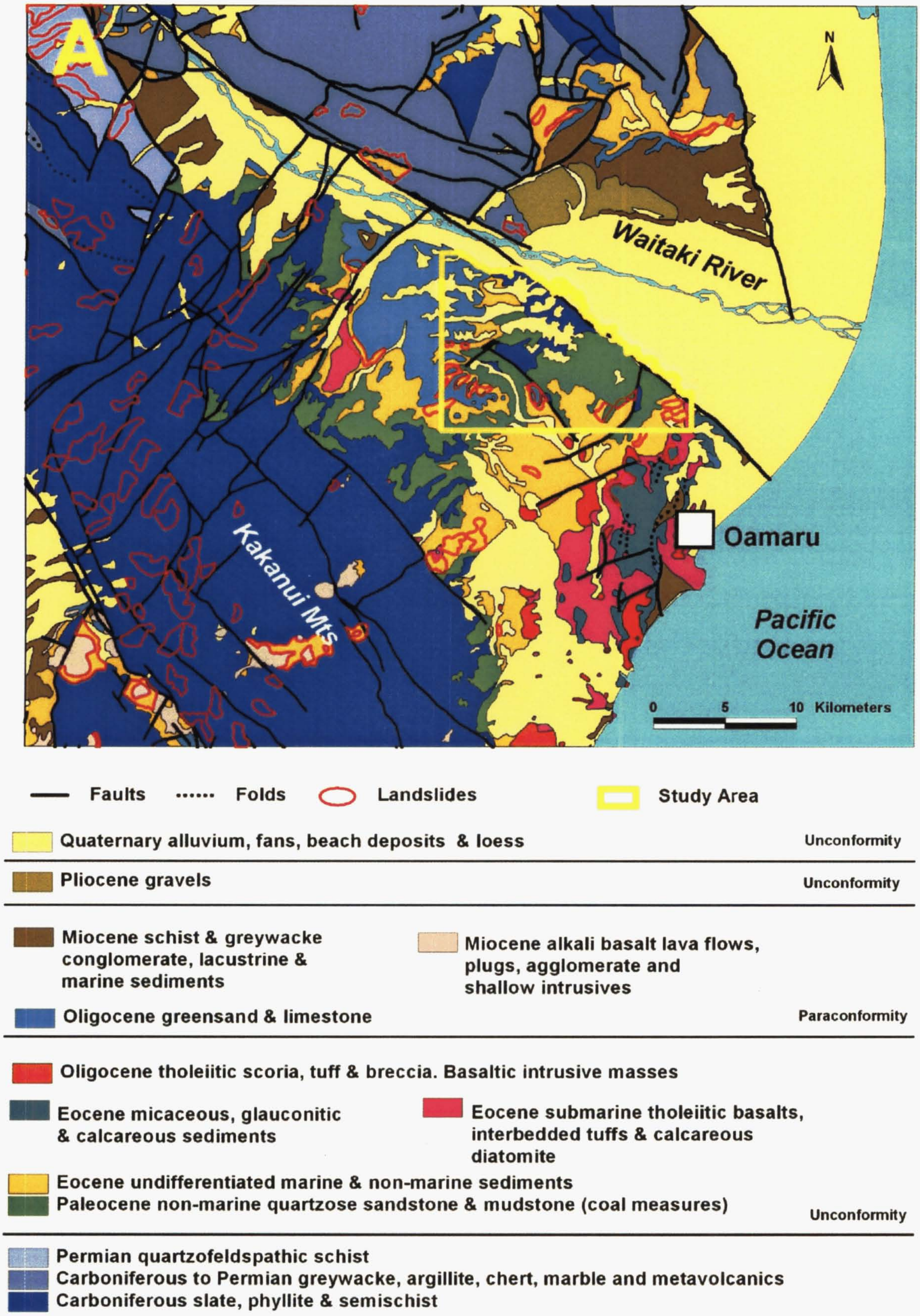
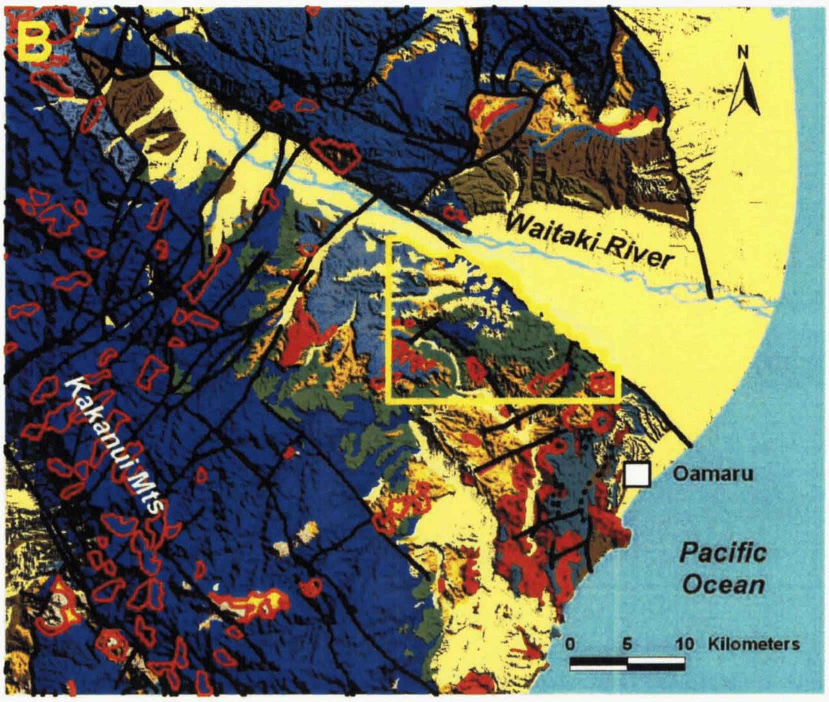


Figure 2.8

A) Geology of North Otago and South Canterbury with the study area indicated. Geological data adapted from Forsyth (2001), originally mapped at scale 1:250,000.

Geological data adapted from Forsyth (2001), originally mapped at scale 1:250,000.



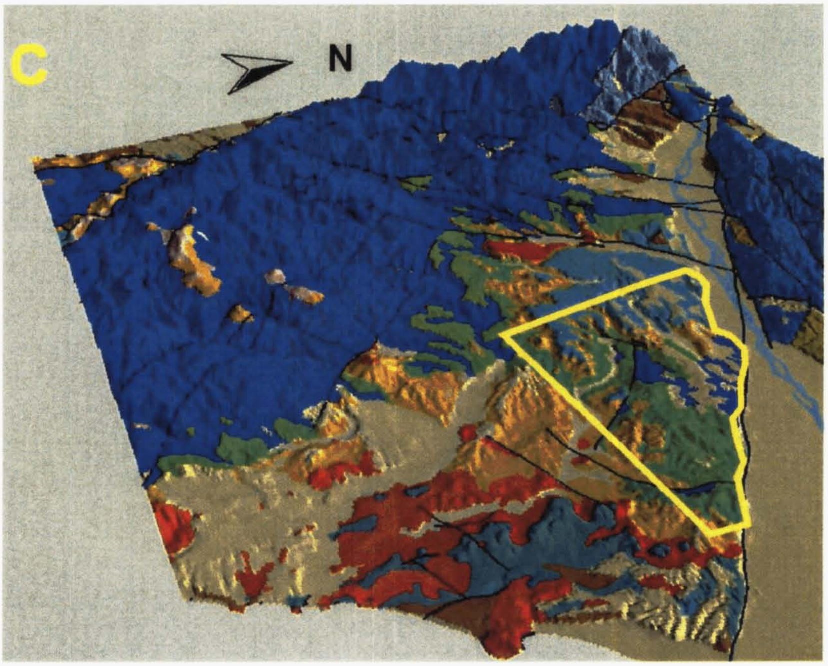


Figure 2.8 continued

B) Geology of North Otago and South Canterbury with the study area indicated, overlain by a shaded digital relief model illuminated from the north-east. Note the difference in shading density between lithological units, implying geological control of slope morphology and landform. See A (previous page) for legend.

C) 3D digital perspective of the geology of North Otago, looking north-west up the lower Waitaki Valley. Note the difference in landform between lithological units. Landslides are not indicated. See A (previous page) for legend.

Geological data adapted from Forsyth (2001), originally mapped at scale 1:250,000.

Table 2.1

Synoptic geological history of the North Otago region after Gage (1957). Epoch & period data are from Forsyth (2001). Lithological units within the study area resulting from particular episodes in the geological history are in bold italics.

Pleistocene	Vigorous orogeny, uplift & erosion. ***Gravels of the High Terraces.***
Miocene	Outpourings of basalt. ***Molehill Basalt.*** Mild orogeny, erosion & peneplanation. Subsidence, rapid accumulation of non-marine clastics. Mild orogeny, emergence & erosion
Oligocene	Subsidence; moderately rapid accumulation of increasingly clastic marine sediments. Slow subsidence; slow accumulation of chiefly calcareous, organic, & chemical marine sediments. Interval of stillstand; non-deposition; solution & boring of substratum, Slow subsidence; accumulation of chiefly calcareous, organic, and minor fine clastic sediment. ***Otekaike Limestone.*** Very slow subsidence; slow accumulation of organic & chemical sediments. Short halt in sedimentation; corrosion & boring of substratum. Slow subsidence; accumulation of calcareous organic marine sediments. ***Kokoamu Greensand.*** Marine planation of volcanoes. Submarine basaltic eruptions. Accumulation of pure calcareous sediment on wave planed volcanic platform. ***McDonald Limestone.*** Submarine basaltic eruptions; intrusion of basalt at shallow depths. ***Waiareka Volcanic Formation.***
Eocene	Subsidence; moderately rapid accumulation of fine marine clastic sediments. ***Raki Siltstone.*** Subsidence; accelerating deposition of chiefly arenaceous marine sediments. ***Tapui Glauconitic Sandstone.*** Long stillstand; possibly emergence; marine planation & boring of substratum. Accumulation of limonitic & micaceous sandstones and siltstones. ***Kauru Formation.***
Paleocene	Oscillatory epeirogenic floodings of peneplain; marine erosion & redeposition of surface materials of peneplain. ***Papakaio Formation.***
Upper Cretaceous	Peneplanation; non-marine accumulation of quartzose lag gravels & sands.
Late Jurassic- Lower Cretaceous	Vigorous orogeny; deformation, uplift & erosion.
Upper Palaeozoic- Lower Jurassic	Regional metamorphism. ***Kakanui Metamorphic Group.*** Sediment accumulation in subduction zone adjacent to Gondwanaland.

The North Otago region is crossed by fault systems with two major orientations: northwest-southeast and northeast-southwest (Figure 2.8). A major fault running northwest-southeast up the lower Waitaki Valley appears to control the orientation of the Waitaki River, and separates the downthrown Waitaki River block from the adjacent North Otago downlands. The downlands block is downthrown with respect to the Kakanui Mountains block, which contains the highest density of faults. Within the study area Marine Isotope Stage 10 fluvial terraces at an elevation of 190 m indicate a local tectonic uplift rate of 0.5 mm yr^{-1}, compared to a coastal uplift rate of 0.04 mm yr^{-1} at Cape Wanbrow based on dating of fossil shells 5 m above sea level (Forsyth, 2001). This order of magnitude difference can be explained by the two areas being separated by faults, with the study area occurring in a zone of more active deformation and resulting uplift. Landslides are also common throughout North Otago, and some are possibly related to seismic events. Clay-rich Tertiary sedimentary units become plastic when wet and are prone to sliding (Forsyth, 2001; Figure 2.9) and landslides can complicate the soil pattern in the area.

Figures 2.8b and 2.8c clearly illustrate the relationship between lithology and landform in the North Otago region. This geological control of landscape morphology can be used to subdivide the region into distinct physiographic units, within which exist similar or repeating suites of landforms. This is discussed in more detail in section 2.5.

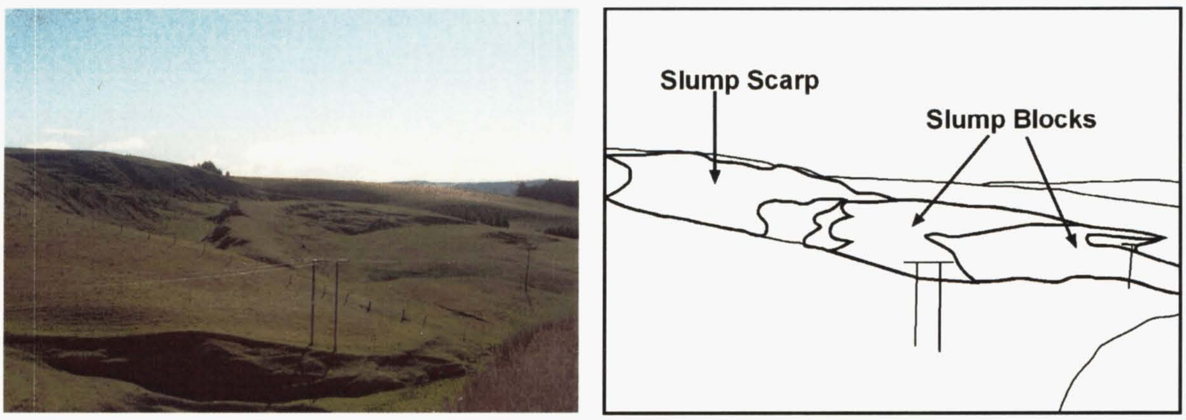


Figure 2.9

Landslide in the study area, exhibiting characteristic slumping mass movement. These failures possibly occur during earthquakes. Landslides such as these can complicate the soil pattern in the landscape.

2.5 Soil Parent Materials

2.5.1 Geological Parent Materials

The largest-scale geological map of the study area was published at 1:63,360 (Gage, 1957; Figure 2.10 and Table 2.2). For the purposes of this study soil parent materials are divided into two classes: the first, geological parent materials, refers to the lithologies mapped by Gage (1957). Whether or not these lithologies actually become parent materials is determined by the thickness of overlying loess, which is the second class of soil parent material (Section 2.5.2). For present purposes, geological parent materials occur where loess coverbeds are less than ~1 m thick.

Figure 2.10 shows the spatial distribution of all lithological units within the study area, and Figures 2.11 to 2.17 illustrate the most significant geological parent materials. Definitions for soil series used to map soils of the study area are principally determined by soil parent material (Wilson, 1970). Distribution of soil taxa, therefore, strongly reflects the geological pattern except for the modifying influence of loess.

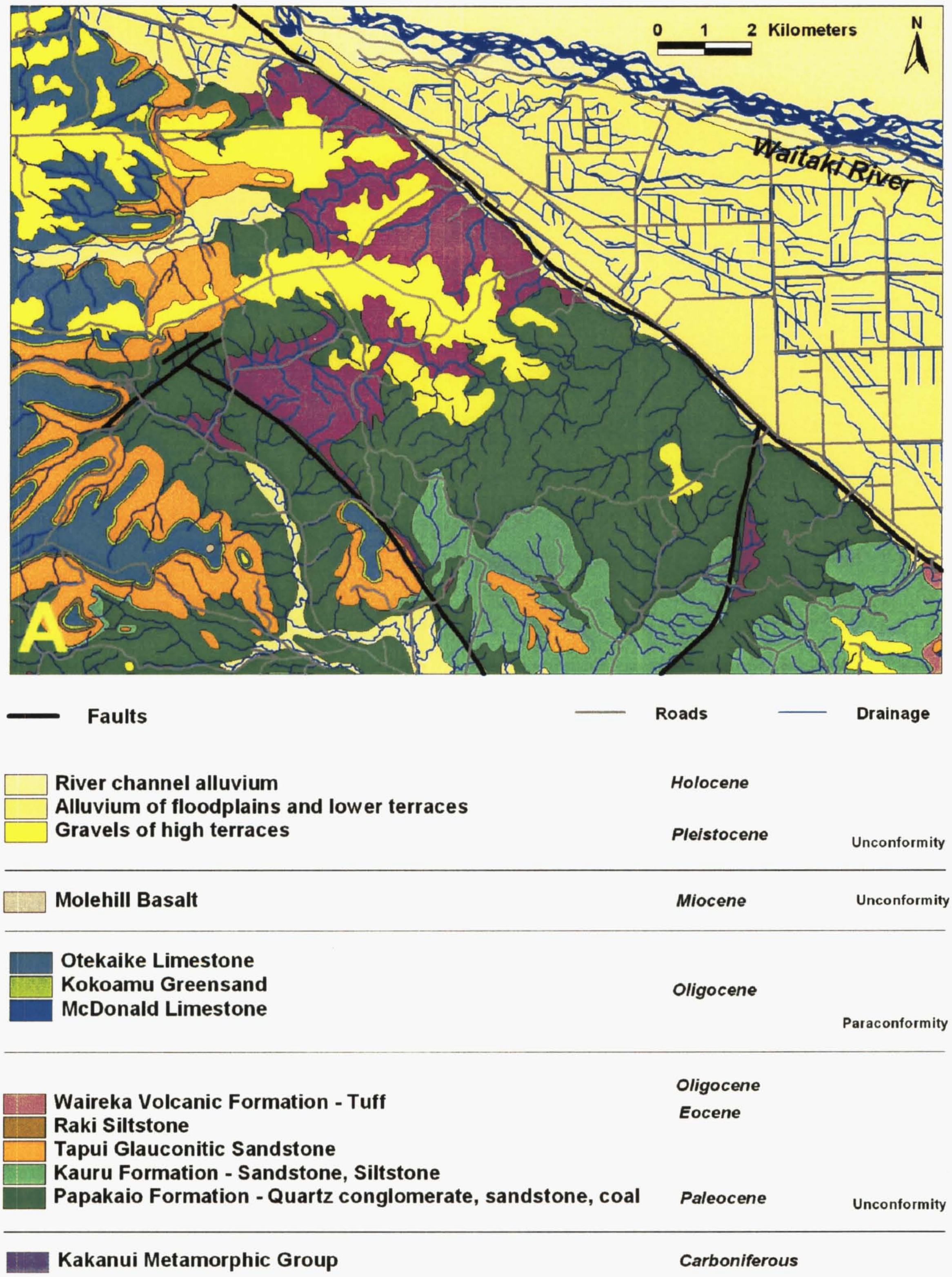
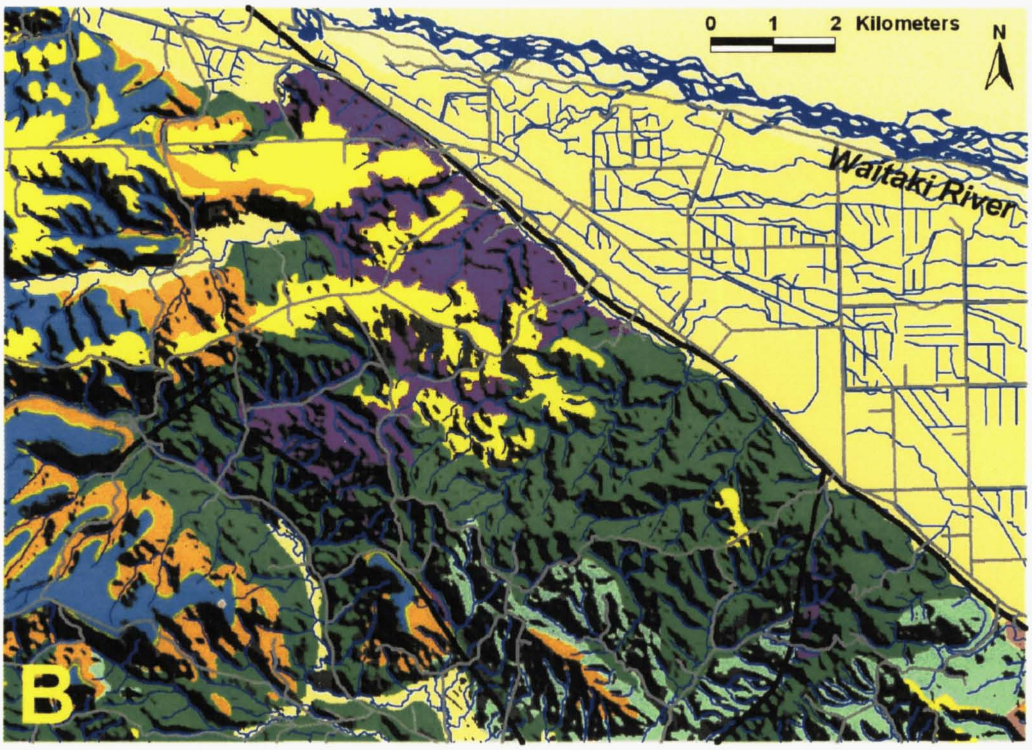


Figure 2.10

A) Geology of the study area. The alluvium of the river channel and of the floodplains are not included in this study.

Lithological data adapted from Gage (1957), originally mapped at scale 1:63,360. Fault, age and unconformity data after Forsyth (2001).



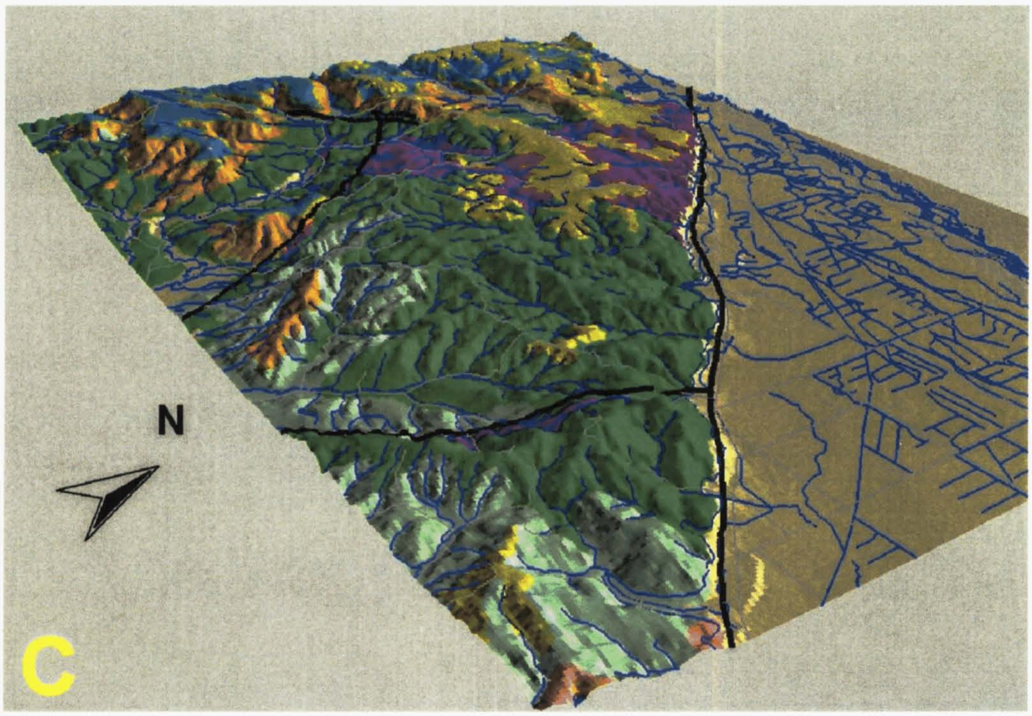


Figure 2.10 continued

B) Geology of the study area, overlain by a shaded digital relief model illuminated from the north-east. Note the difference in shading density between lithological units, implying geological control of slope morphology and landform. See A (previous page) for legend.

C) 3D digital perspective of the geology of the study area, looking north-west. Note the difference in landform between lithological units. See A (previous page) for legend.

Lithological data adapted from Gage (1957), originally mapped at scale 1:63,360. Fault data from Forsyth (2001).

Table 2.2

Lithological units in the study area with their contents and thicknesses, after Gage (1957). Epoch/Period data and unconformity data from Forsyth (2001).

Lithological Unit	Content	Thickness (m)	Epoch/Period
Waitaki River Channel Alluvium	Predominantly greywacke cobbles	?	Holocene
Alluvium of Floodplains & Low Terraces	Predominantly derived from Tertiary sediments.	?	
Gravels of the High Terraces	Predominantly greywacke cobbles with occasional pebbles of quartz & jaspilite	20	Pleistocene
			Unconformity
Molehill Basalt	Volcanic breccias, lava sheets & volcanic plugs.	?	Miocene
			Unconformity
Otekaike Limestone	Hard, massive, semicrystalline to sandy granular glauconitic limestone.	2-5	Oligocene
Kokoamu Greensand	Massive, pure greensand & very glauconitic sand.	1-10	
McDonald Limestone	Hard, massive, finely granular to semicrystalline limestone.	0.3-10	
			Paraconformity
Waiareka Volcanic Formation	Pyroclastic & eruptive basalt, with lenses of chalk & diatomite.	~150	Oligocene
Raki Siltstone	Massive, slightly micaceous silt and fine sand.	2-20	Eocene
Tapui Glauconitic Sandstone	***Top*** Greensand; Sand; ***Bottom*** Glauconitic sand.	~30	
Kauru Formation	***Top*** Glauconitic sands; Silt; ***Bottom*** Concretionary Sandstone.	?	
Papakaio Formation	***Top*** Quartz sand & conglomerate; Coal, carbonaceous silt & clay; Quartz conglomerate; ***Bottom*** Conglomerate, mainly of quartz with minor amounts of schist & greywacke.	~130	Paleocene
			Unconformity
Kakanui Metamorphic Group	Strongly cleaved, nonfoliated fine- to medium- grained, low rank schist alternating with bands of phyllite & schist (semischist).	>3000	Carboniferous

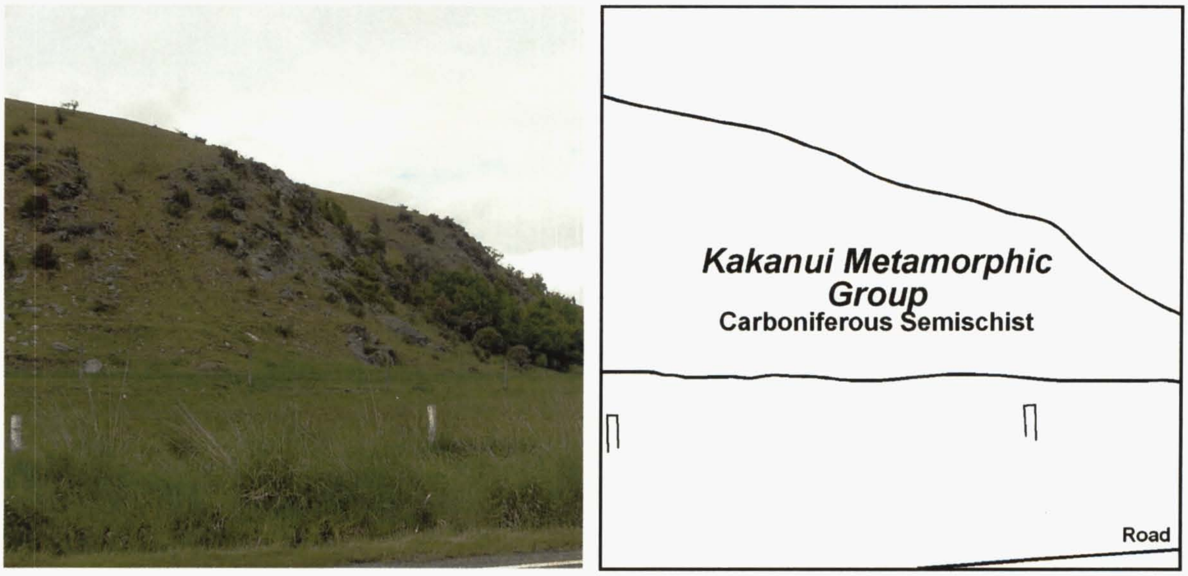


Figure 2.11

The Kakanui Metamorphic Group, comprising the bluffs of the downlands margin to the south of the Waitaki River. Bortons Soils have formed in the phyllite and semischist.

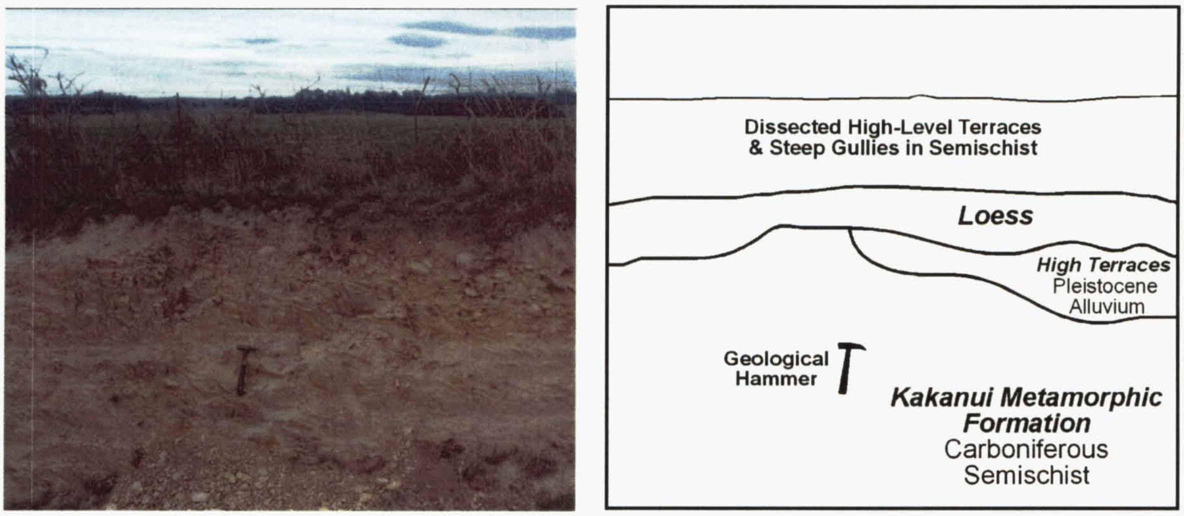


Figure 2.12

Road cut showing the contact between Pleistocene alluvium of the High Terraces and underlying Carboniferous semischist of the Kakanui Metamorphic Group, with both mantled by thin loess. A Bortons Soil has formed on the thin loess over semischist, and a Taiko Soil has formed on the thin loess over Pleistocene alluvium.

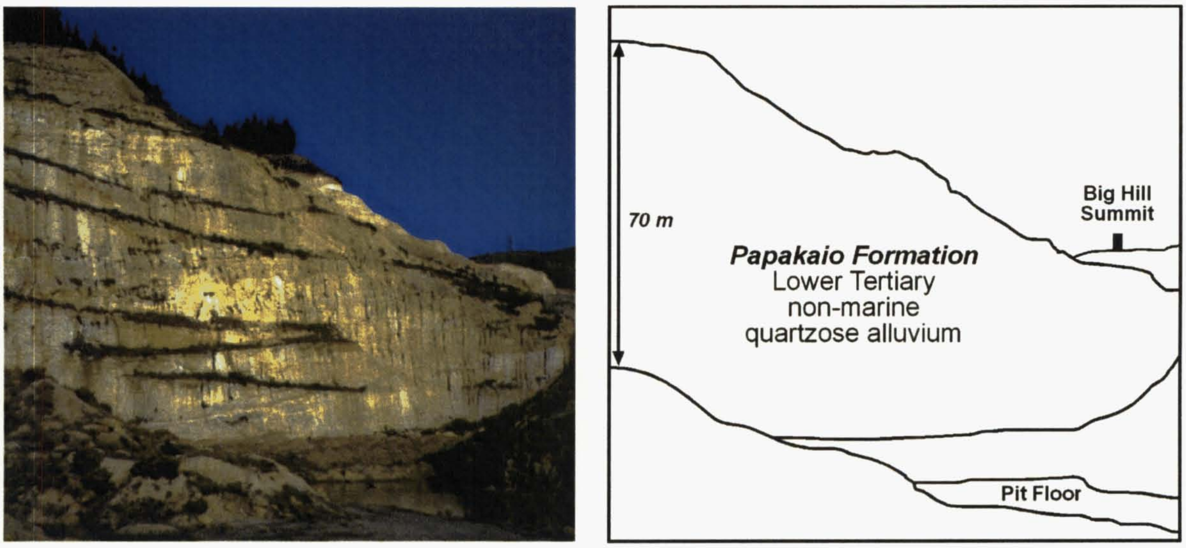


Figure 2.13

Gravel pit exposure showing the Papakaio Formation, the lower Tertiary non-marine quartzose alluvium underlying much of the study area. Papakaio Soils have formed on the quartzose alluvium. Big Hill, the highest elevation point in the study area, is in the background.

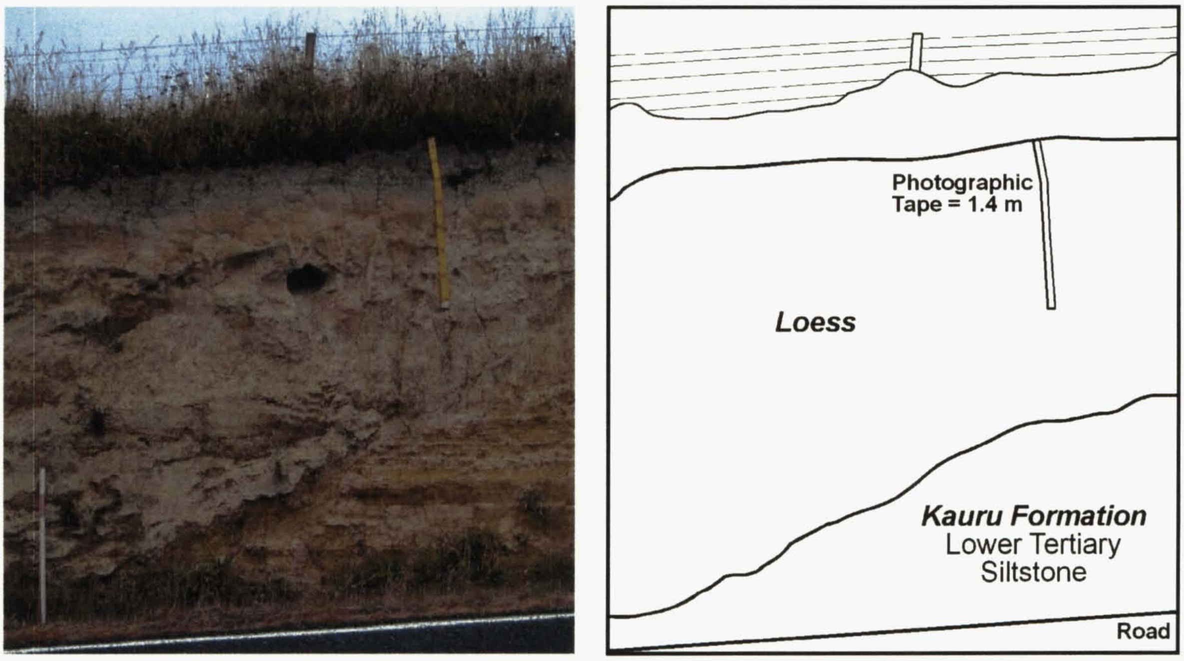


Figure 2.14

Road cut showing Lower Tertiary siltstone within the Kauru Formation overlain by loess, on which a Timaru Soil has formed. Where loess is thin to absent, Airedale Soils form on the siltstone.

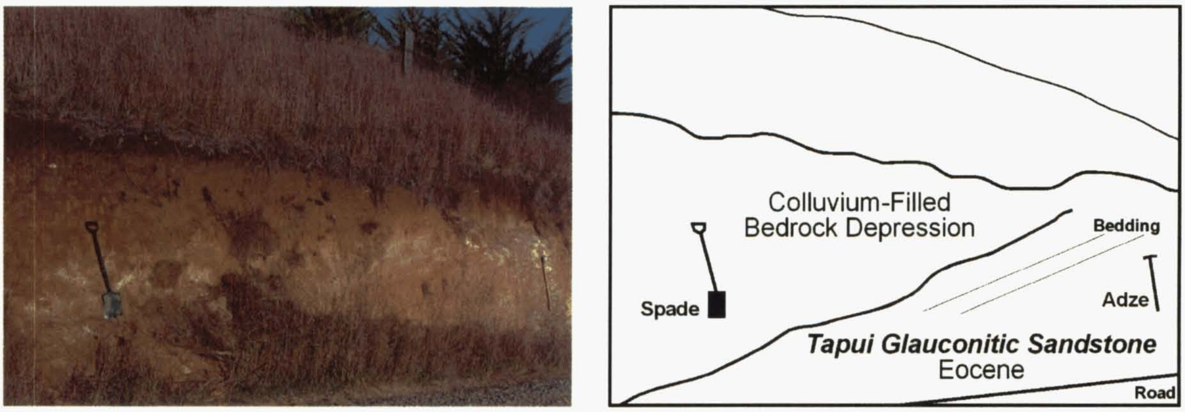


Figure 2.15

Road cut showing the Eocene Tapui Glauconitic Sandstone with bedding dipping to the left, truncated by a glauconitic sandstone and limestone colluvium-filled bedrock depression. Tokarahi Soils have formed on both the colluvium and the consolidated sediments.

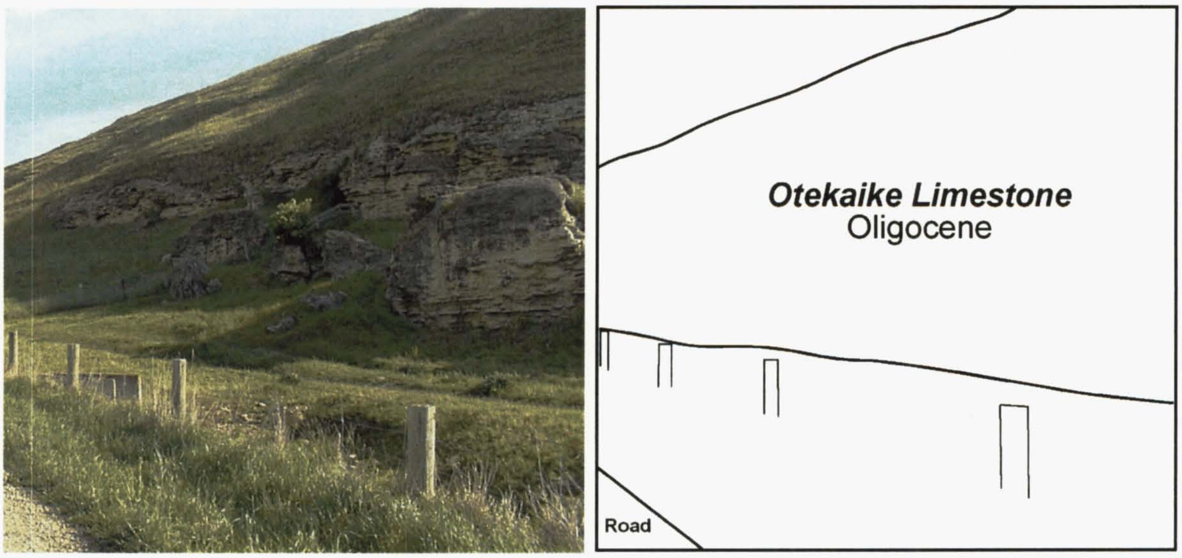


Figure 2.16

Oligocene Otekaike Limestone, with characteristic "flaggy" weathering. Waikakahi Soils have formed on the slopes shown here.

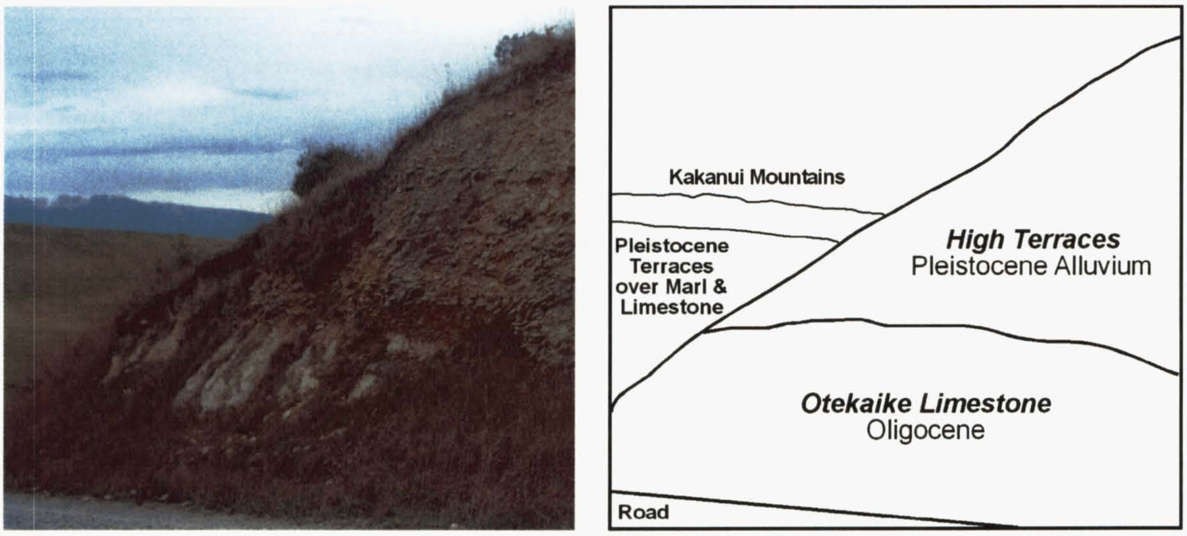


Figure 2.17

Road cut showing the contact between Pleistocene alluvium of the High Terraces and underlying Oligocene Otekaike Limestone. A Taiko Soil has formed on the Pleistocene Alluvium.

2.5.2 Loess

Loess, as defined by Pye (1987), is a terrestrial wind-blown deposit consisting chiefly of quartz, feldspar, mica, clay minerals and carbonate grains in varying proportions. Heavy minerals, phytoliths, salts and volcanic ash shards are also sometimes important constituents (Pye, 1987). The term *loess* is derived from the German verb *lősen* – to loosen – and reflects the dominantly porous, loose and crumbly nature of most European loess, which has served as the material upon which loess definitions have traditionally been based (Raeside, 1964; Selby, 1976). As described by Raeside (1964) however, New Zealand loess is generally compact and of low permeability, particularly in the South Island. The definition of loess used here will be that of Raeside (1964); the term *loess* will be used to describe any deposit of aeolian origin other than sand dunes where transport has been primarily by suspension, and consisting of fine sandy loam texture or finer. Where loess is recognised in the landscape it can be subdivided into either primary loess where deposition and accumulation have occurred in the same location, or re-deposited loess where primary loess has been eroded and re-deposited by running water and/or slope processes (Pye, 1987). Ngapara and Timaru Soils in the study area are formed in primary loess, and Brookstead and Ardgowan Soils are formed in colluvial/slopewashed loess (see Section 2.7).

In the absence of data describing loess distribution in North Otago, an attempt has been made here to use the soil map data of Soil Bureau Staff (1968) and Wilson (1970) as a substitute. While this technique is obviously subject to criticism, particularly with respect to the quality of the soil data used, it is not without precedent (Mason, 1999). Soils that by definition occurred on loessial parent materials were amalgamated and reclassified as loess. This technique is used here not to definitively describe loess distribution, but to provide an example of how other existing data sets may be employed for purposes other than those for which they were designed.

Figure 2.18 shows North Otago loess depth data from Young (1964), underlain by loess distribution data inferred from Soil Bureau Staff (1968, originally mapped at scale 1: 253,440). Young (1964) documented the petrography and stratigraphy of loess in North Otago, and the 64 point measurements of loess thickness made by him are plotted in Figure 2.18. Loess is absent to thin (< 1m) both on the Waitaki River floodplain and closer to the Kakanui Mountains, and ranges in depth from 1-12 m elsewhere on the downlands. Accumulations of slopewashed loess provide over-thickened loess deposits both on the downlands margin (> 2 m) and on the coast (2 - >2.3 m). The loess distribution inferred from Soil Bureau Staff (1968) indicates the presence of loess on the alluvial plains of the Waitaki River and the coastal plain of Oamaru, as well as on most of the North Otago downlands (Figure 2.18). Loess is absent on some valley sides, on low terraces and on the present river floodplains, from where it has been eroded (Young, 1964; Wilson, 1973). Loess is also absent on the higher elevations of the Kakanui Mountains (over 500 m)

Figure 2.19 shows the loess distribution in the study area inferred from the soil data of Wilson (1970, originally mapped at scale 1:50,000) in the same manner that loess distribution in North Otago was inferred from Soil Bureau Staff (1968). The increase in scale (from 1:253,440 to 1:50,000) better resolves SMUs and therefore the resulting inferred loess distribution. Only those soil series that by definition exist on loessial parent materials (>1.5 m) depth were used, and this includes both primary and colluvial/slopewashed loess. The inferred distribution (Figure 2.19) shows loess parent materials present on flat surfaces in the northern and southwestern parts of the study area, as well as in the more dissected region in the central and eastern parts of the study area. Loess parent materials are absent in those areas with steeper slopes and active stream channels. According to Young (1964) there is little doubt that during periods of maximum deposition, loess was laid down as a blanket covering the whole area, and its present distribution is generally consistent with this. The depth of loess varies with surface age and the degree of erosion (Wilson, 1973), and dissection has caused a marked variation in thickness over a short distance in some localities (Young, 1964).

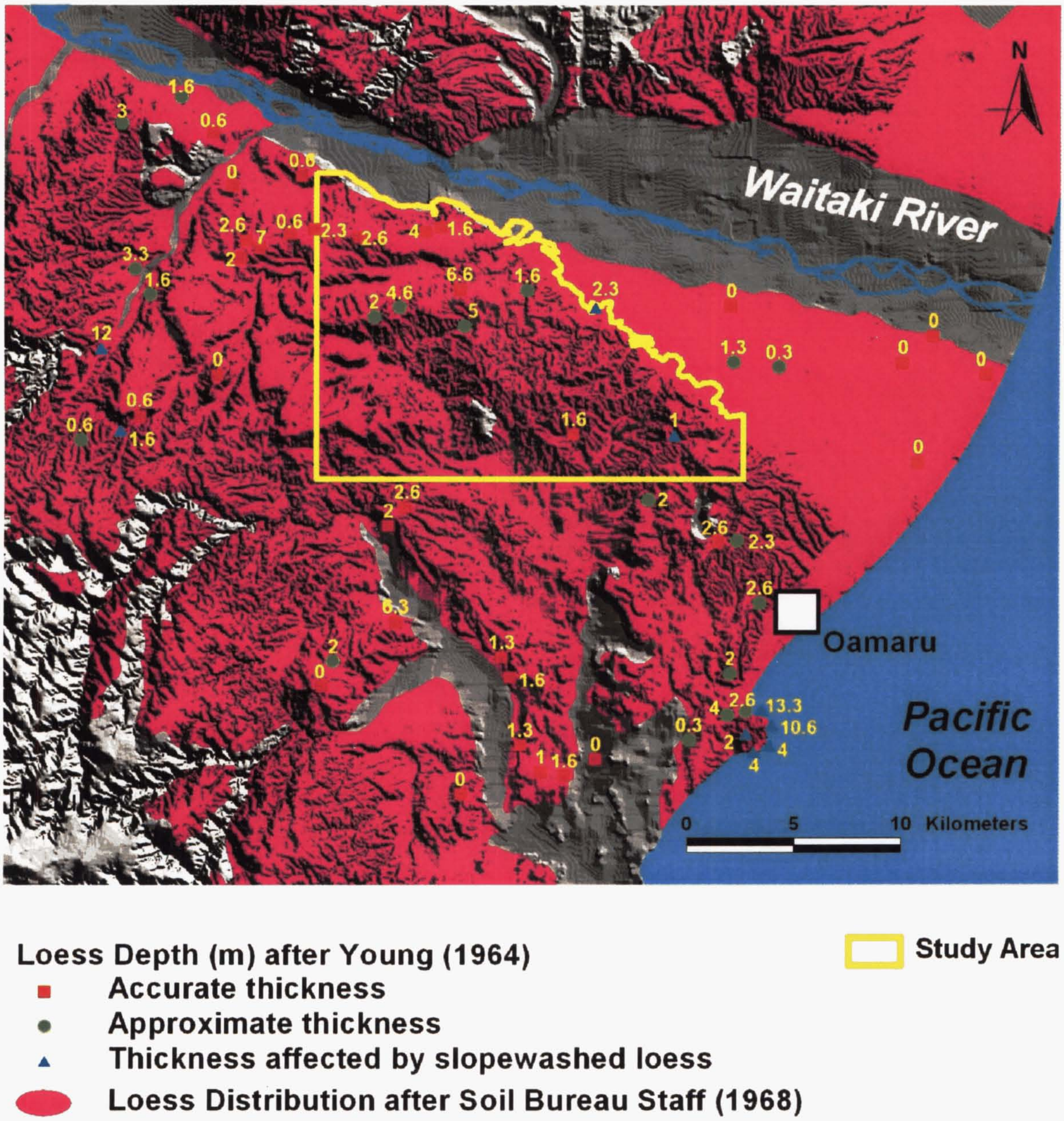


Figure 2.18

Locations in North Otago where loess depth (m) was measured by Young (1964), underlain by the loess distribution inferred from Soil Bureau Staff (1968). Note the *absence* of loess as indicated by Young (0 m) occurring where the *presence* of loess is inferred from Soil Survey Staff (1968). This highlights one problem in adapting pre-existing databases to purposes for which they were not designed.

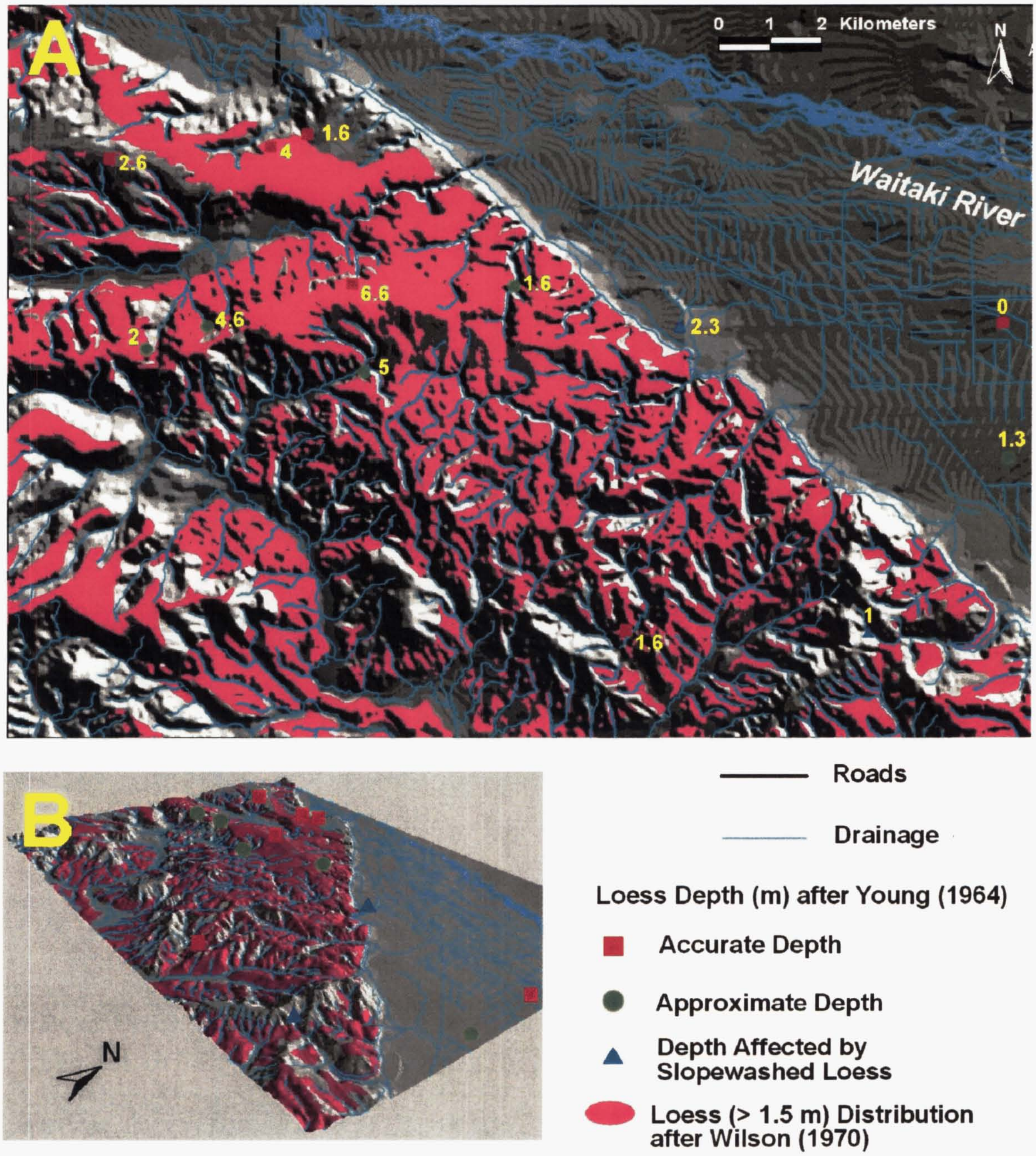


Figure 2.19

A) Locations in the study area on the Waitaki River floodplain where loess depth was measured by Young (1964), underlain by the loess distribution (>1.5 m) inferred from Wilson (1970). Note the *presence* of loess at some locations as indicated by Young (1964) where the *absence* of loess (>1.5 m) is inferred from Wilson (1970).

B) 3D digital perspective of the loess (>1.5 m depth) distribution in the study area inferred from Wilson (1970), looking north-west. The locations of Young's observations are indicated. See A) for depths.

The loess of North Otago is derived from Rakaia terrane rocks and subsidiary ranges (Forsyth, 2001), and the loess is therefore dominantly quartzofeldspathic in composition. Quartz is the predominant mineral present (50-70%) followed by feldspar (25-35%), with the remainder composed of micas and "heavier" minerals such as epidote, horneblende and zircon (Young, 1964). The quartzofelpathic nature of the loess means that it is an essentially nutrient-poor parent material compared to the generally nutrient-rich geological parent materials (glauconitic sandstones, greensands and limestones). The small amounts of Fe oxides and Ca also contribute to a general poor subsoil structure, although post-depositional weathering has increased the amounts of limonite present in some deeper loess sections (Young, 1964).

The textural variation in the loess parent materials plays a significant role in soil development in the study area. Textural variation is consistent with downwind fining from the source area (Ruhe, 1969). Loess becomes uniformly finer with approach to the coast and with increasing distance from the Waitaki River, and the most uniform decrease in median particle diameter approximately parallels the strongest present-day wind, the northwesterly (Young, 1964; Wilson, 1973). This uniform textural variation from coarser loess to finer loess with increasing distance from the primary loess source is reflected in the delineation of soil taxa (Wilson, 1970). Soils formed in coarse primary and colluvial/slopewashed loess (Ngapara and Brookstead Soils, respectively) are mapped in the north-western part of the study area, which is near to the Waitaki River, and soils formed in finer primary and colluvial/slopewashed loess (Timaru and Ardgowan Soils, respectively) are mapped in the south-eastern part of the study area, further away from the river.

The role of loess texture in soil development is most evident in subsoils of the Ngapara and Timaru soil series. A fragipan is absent in the coarser-textured Ngapara Soils, but present in the finer-textured Timaru Soils. Whether fragipan formation is primarily a result of decreased soil bioturbation in glacial periods (Raeside, 1964) or is the manifestation of soil collapse due to hydroconsolidation (Assallay, 1998), it is clear that fragipan formation and preservation is correlated with finer-textured loess. As a result, the Timaru soils with their dense fragic subsoils, show characteristic mottling and perch-gley features. The Ardgowan Soils formed in finer colluvial/slopewashed loess do not tend to exhibit fragic properties, for their largely unstable nature appears to inhibit fragipan formation or persistence.

As noted above, loess thickness varies with surface age and stability, and dissection has caused a marked variation in loess thickness over a short distance in some localities. The amount of loess present is dependent upon the total loess accumulation, which is the sum of loess deposition and erosion - the exact amounts of which are usually unknown (Goossens, 2001). The primary determinants of loess accumulation are wind speed (Figure 2.20), rainfall (Figure 2.4) and the terrain characteristics of the deposition surface (see Section 2.6). With the advent of digital databases quantitatively describing these primary determinants, an interesting opportunity exists in North Otago for future research into the processes of loess accumulation and landscape evolution, and also for an expansion of the loess-stratigraphic studies of Young (1964).

For the present work, the nature of loess distribution is an essential element in the development of quantitative SLMs for the study area. The spatial distribution of soil series in the study area is strongly influenced by loess distribution. The quantitative modelling of loess distribution based upon existing soil maps, and based upon field data collected for the present work, is described in Chapters 4 and 5 respectively.

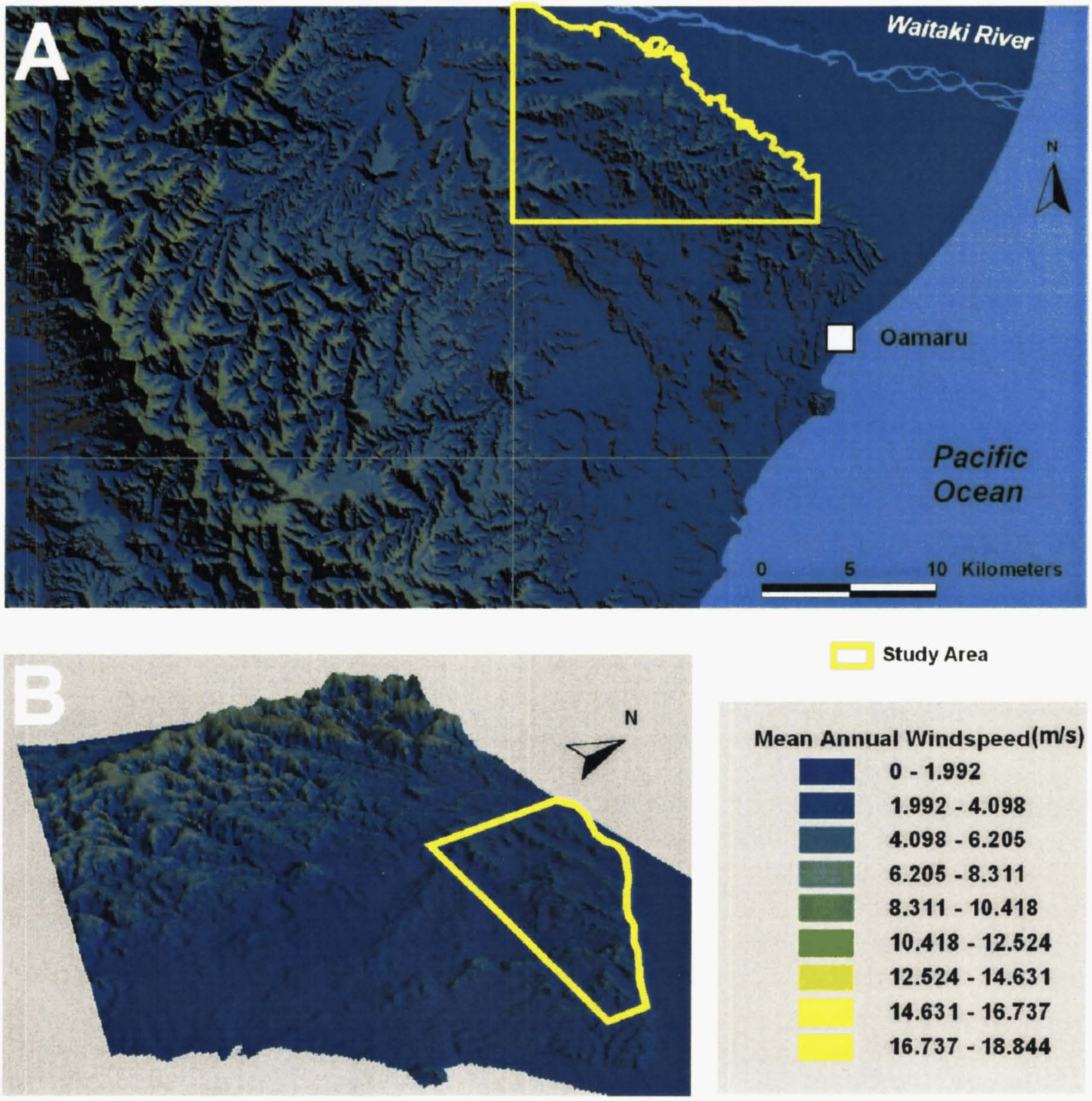


Figure 2.20

A) Mean annual windspeed (m/s) in North Otago, overlain by a shaded digital relief model illuminated from the north-east. The study area is indicated. Note the increase in mean windspeed with increasing elevation. Loess deposition and accumulation are influenced by windspeed.

B) 3D digital perspective of the mean annual windspeed of North Otago, looking north-west up the lower Waitaki Valley. The study area is indicated.

Climate data from NIWA (2001).

2.6 Physiography

The North Otago region can be subdivided into physiographic regions, within which characteristic sets of similar or repeating landforms occur. Consistent associations of soil series exist on these landforms, and therefore physiographic regions can delineate the spatial extent of these soil associations. The combination of physiographic region delineations, quantitative SLMs and digital microclimate data (*e.g.* Figure 2.4) has the potential to more objectively define land systems (see Section 1.2.4; Christian and Stewart, 1953; Gibbons and Downes, 1964).

The physiographic units described here are a synthesis of topographic, dissection and to some extent climatic patterns designed to provide a qualitative understanding of the landscape. They are not used in the development of the quantitative SLMs presented in Chapters 4 and 5 because they were considered to be an unwanted, highly subjective, classification imposed upon the landscape. However, the physiographic regions delineated within the study area have been used as the basis for the soil map legends.

The physiographic regions for North Otago (Figure 2.21) and the study area (Figure 2.23) have been delineated using the geological data of Forsyth (2001) and Gage (1957), digital terrain analysis and visual inspection of the digital shaded relief model based on a 25m DEM for the area. The use of digital shaded relief data in particular for the delineation of physiographic units is largely subjective, but is useful. A more objective representation of physiographic regions might utilise quantitative drainage network analysis. This approach would be useful for objective delineation of physiographic regions, given the readily apparent differences in drainage densities between regions evident in Figures 2.21 and 2.23, and might prove beneficial for future research.

The physiographic regions of North Otago are shown in Figure 2.21 and their defining characteristics are listed in Table 2.3. Mean slope values derived from a 25 m DEM of the area are included and show significant differences between physiographic regions. A comparison of slope class distributions between physiographic regions is shown in Figure 2.22. The highest modal slopes occur in the Kakanui Mountains (20-25°), with the Late-Cretaceous Peneplain also showing a range of higher slope classes reflecting the dissected nature of this region. More than half of the Loess-Mantled Downlands are comprised of slopes in the 0-5° class, with the remainder dominated by the 5-10° and 10-15° classes. The Mesas, Cuestas and Buttes region is dominated by slopes in the 5-10° class the next most significant range of slopes being 0-5°. The remaining physiographic regions –

Dissected High-Level Terraces, Alluvial Plains (Tertiary Sediments) and Alluvial Plains (Quaternary Greywacke Alluvium) are dominantly comprised of slopes in the 0-5° class.

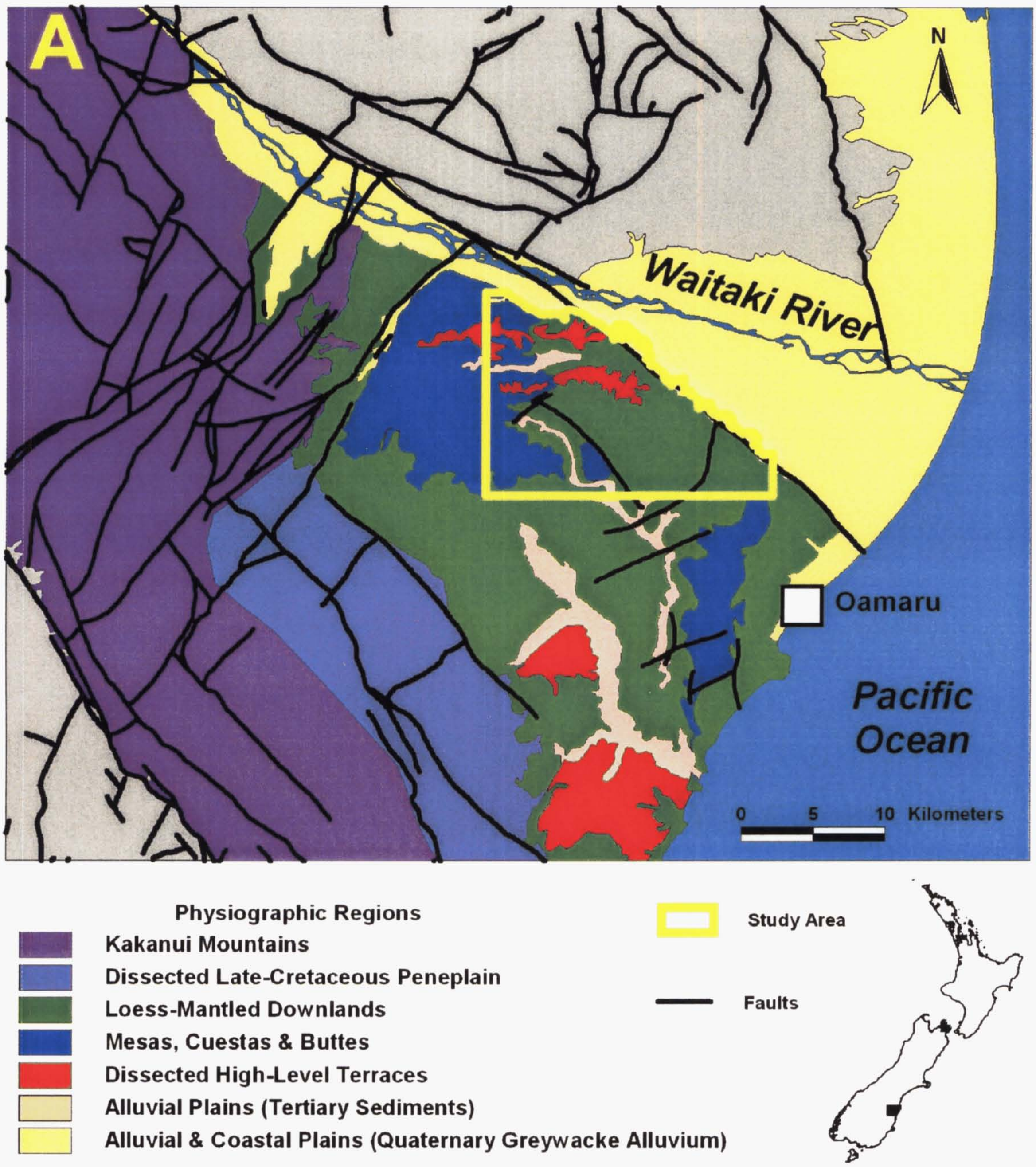


Figure 2.21

A) Physiographic regions of North Otago including the Kakanui Mountains and the Coastal Plain north of the Waitaki River. The study area and faults (from Forsyth, 2001) are indicated.

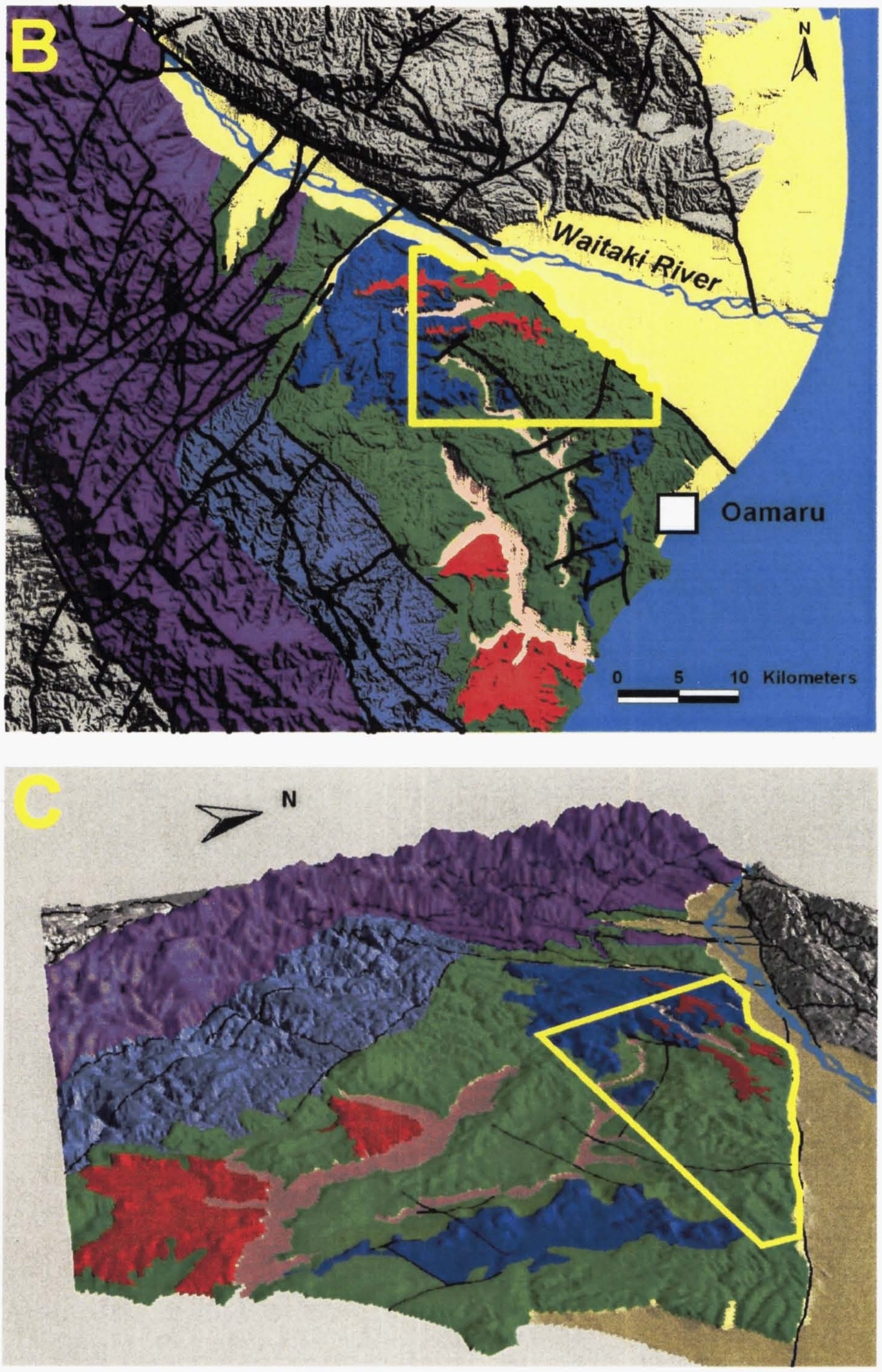


Figure 2.21 continued

B) Physiographic regions of North Otago including the Kakanui Mountains and the Coastal Plain north of the Waitaki River, overlain by a shaded digital relief model illuminated from the north-east. The study area and faults (from Forsyth, 2001) are indicated. See A (previous page) for legend.

C) 3D digital perspective of the physiographic regions of North Otago, looking north-west up the lower Waitaki Valley. The study area and faults (from Forsyth, 2001) are indicated. See A (previous page) for legend.

Table 2.3

Defining features of physiographic regions in North Otago. Mean slope values derived from randomised sample (n = 1000 for each region) of grid derived from 25 m DEM. F = 1703, Sig. = 0.000.

Physiographic Region	**Defining Features**	**Mean Slope (°)**
Kakanui Mountains	Highly faulted, heavily dissected semischist mountains.	20
Dissected Late-Cretaceous Peneplain	Dissected, fault-bounded former erosion surface on semischist with broad interfluves & steep gullies.	16
Loess-Mantled Downlands	Easy to rolling country on Tertiary rocks covered with varying depths of loess.	6
Mesas, Cuestas & Buttes	Structural landforms with hard limestone cap rocks & associated scarp slopes & dip slopes.	5
Dissected High-Level Terraces	Dissected and loess-mantled (patchy) terraces forming plateaux in the downlands underlain by Pleistocene greywacke alluvium.	1
Alluvial Plains (Tertiary Sediments)	Valley fill deposits occurring within the downlands, with alluvium sourced from Tertiary sediments.	1
Alluvial Plains (Quaternary Greywacke Alluvium)	Low-relief floodplain of the Waitaki River & Oamaru coastal plain composed of greywacke alluvium.	3

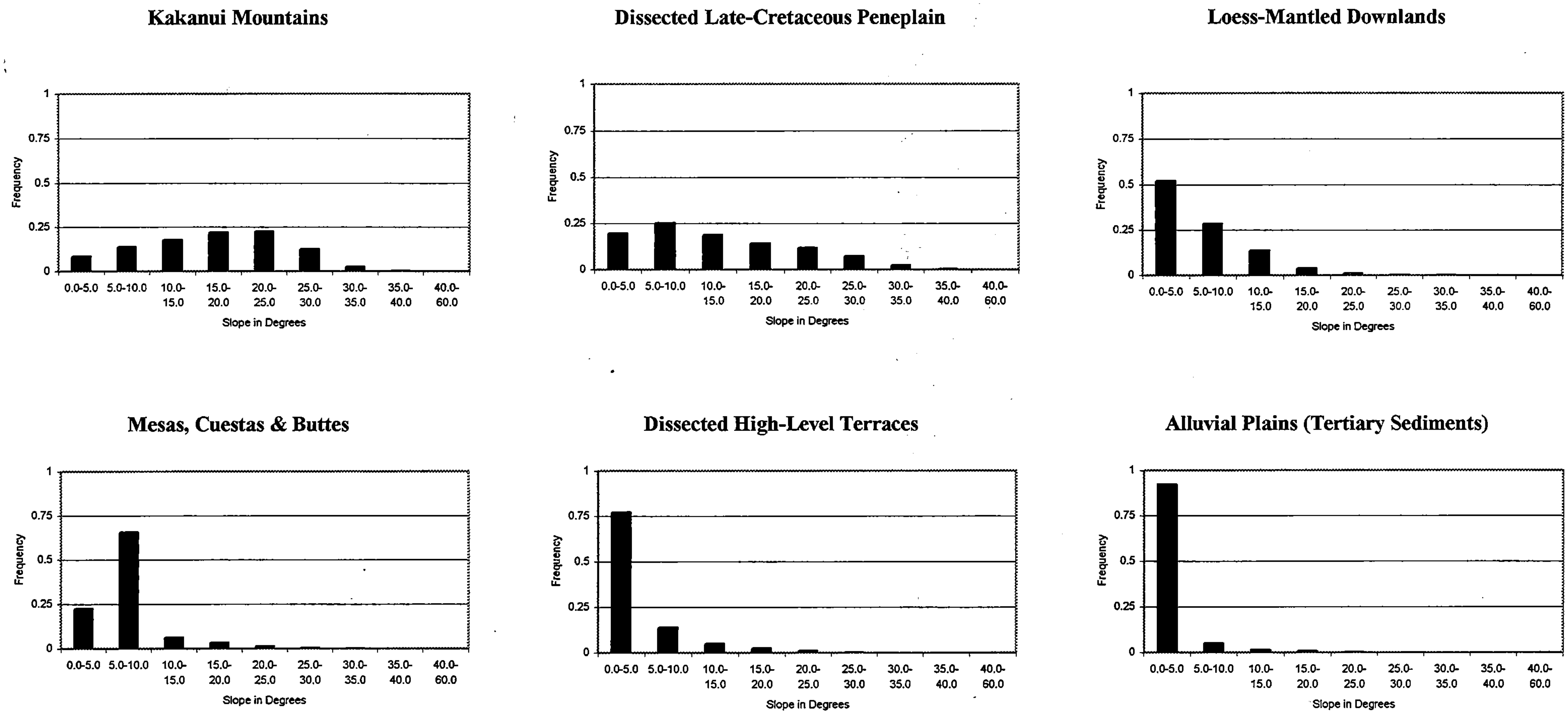


Figure 2.22

Slope class distributions (derived from a 25 m DEM) for physiographic regions of North Otago.

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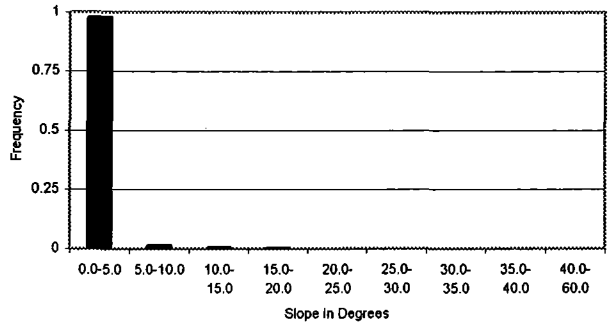


Physiographic regions within the study area were developed in a similar way to that described for the North Otago region, but at a higher resolution (Figure 2.23). These physiographic regions are generally representative of the physiographic regions delineated for wider North Otago. The Loess-Mantled Dissected Hill Country is a part of the wider Loess-Mantled Downlands, yet is underlain by more heavily dissected and erodible Lower Tertiary sediments, and has been labelled accordingly. Defining characteristics are listed in Table 2.4, with mean slope values derived from a 25 m DEM of the area showing significant differences between physiographic regions. A comparison of slope class distributions between physiographic regions is shown in Figure 2.24. Most of the slopes in the Steep Gullies in Schist region were in the 0-5° and 5-10° classes, but slopes ranged up to 35°. The modal slopes for both the Loess-Mantled Dissected Hill Country and Mesas and Buttes were in the 5-10° range, but these physiographic regions also showed a wide range in slope classes reflecting the dissected nature of the former and presence of scarp slopes in the latter. Slopes in the 0-5° class dominated the Dissected High-Level Terraces, Alluvial Plains (Tertiary Sediments) and Fans on the Downlands Margin adjacent to the Waitaki alluvial plain. The inclusion of high slope values in the latter two regions most likely reflects the erroneous inclusion of steeper slopes within the delineation of these units due to boundary inaccuracies, and artefacts in the DEM.

Figures 2.25 – 2.27 show panoramic photographs of the various physiographic regions within the study area, accompanied by digital 3D perspectives based upon 25 m DEM data. Although "smoothing" associated with digitally modelling the landscape is evident, and is a likely source of error in terrain analysis, geological and DEM data can be used effectively to subdivide the landscape into physiographic units. The value of these units as domains for distinct SLMs was not investigated in this study.

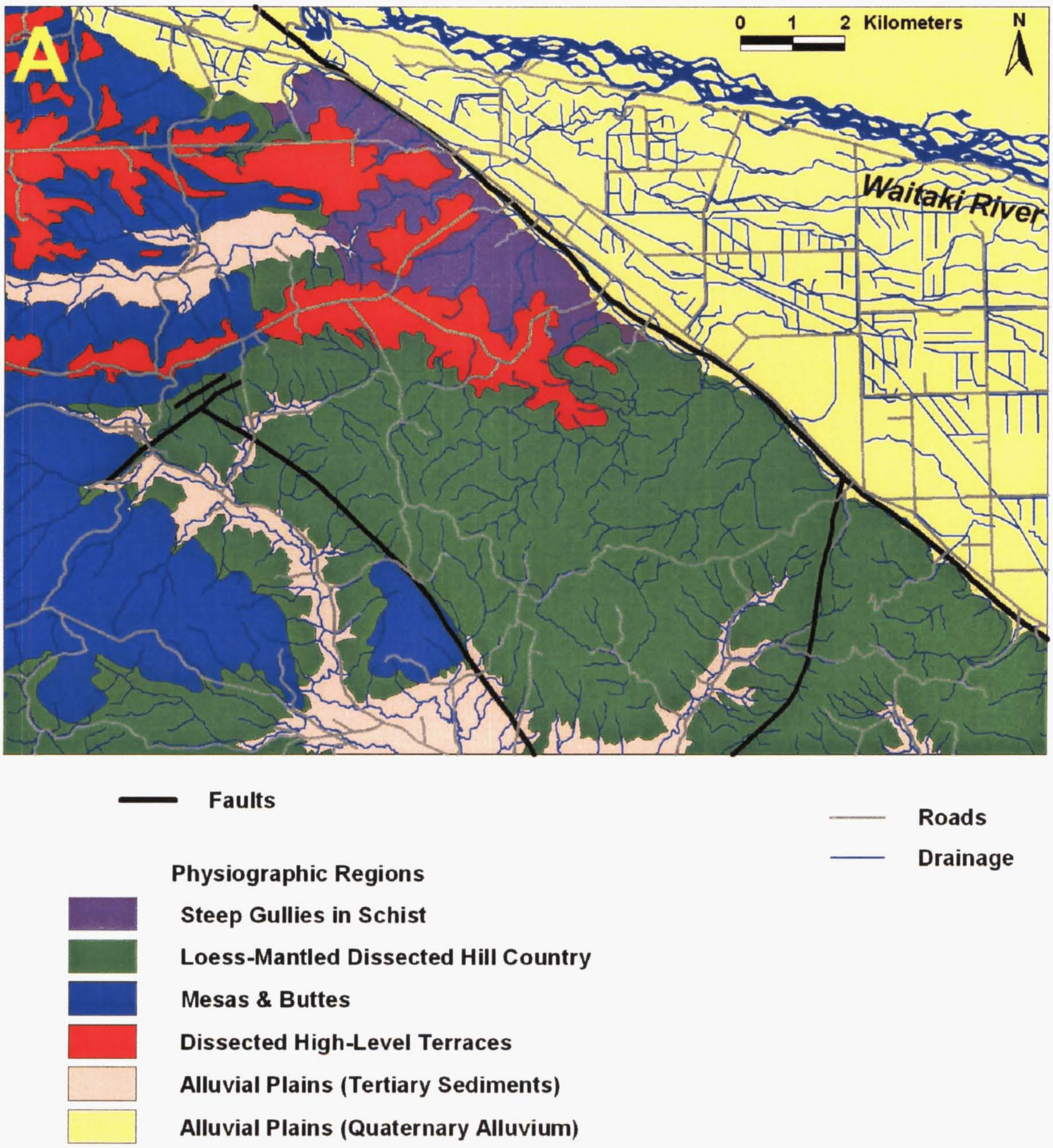
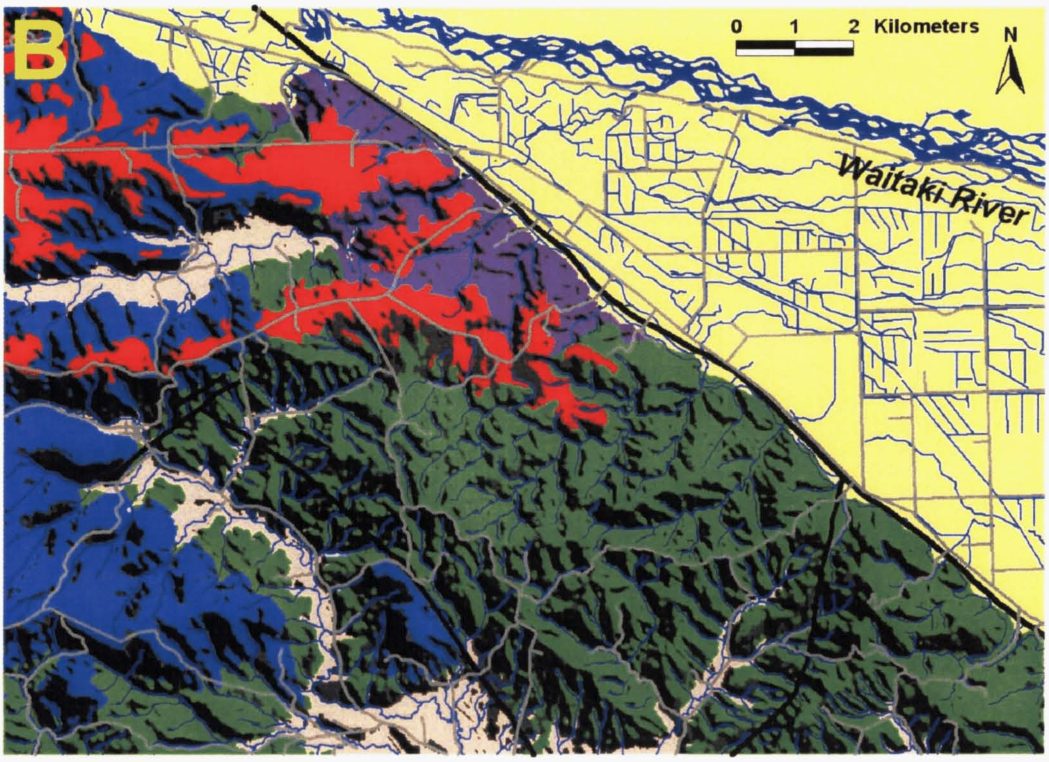


Figure 2.23

A) Physiographic regions within the study area, excluding the Quaternary greywacke alluvium of the Waitaki River alluvial plain. Faults (after Forsyth, 2001) are shown.



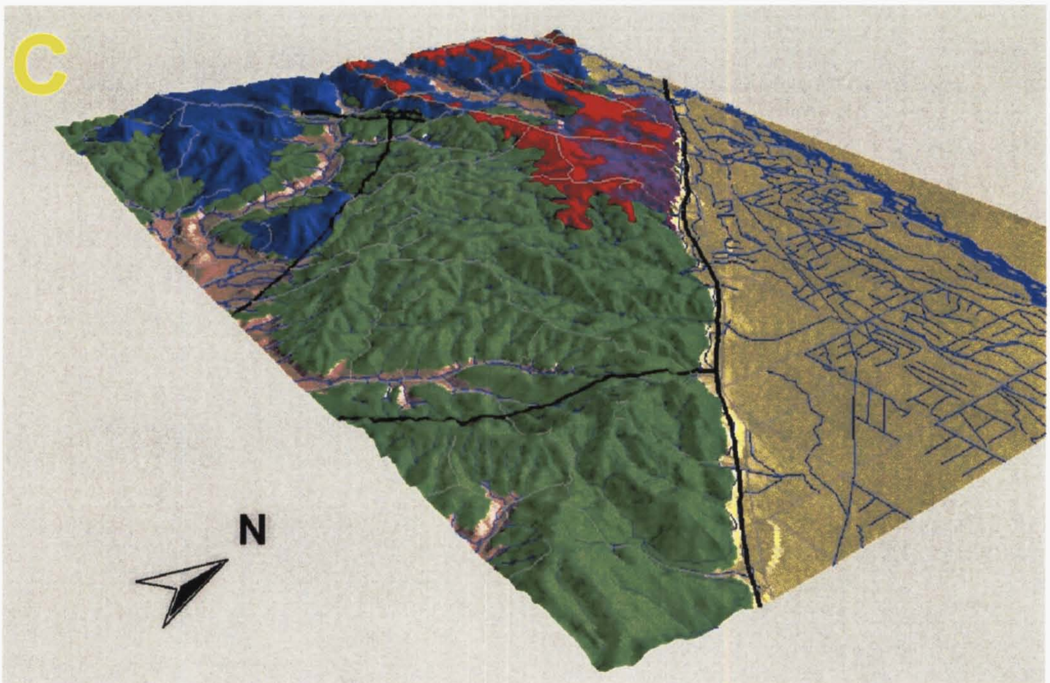


Figure 2.23 continued

B) Physiographic regions within the study area, excluding the Quaternary greywacke alluvium of the Waitaki River alluvial plain, overlain by a shaded digital relief model illuminated from the north-east. See A (previous page) for legend. Faults (after Forsyth, 2001) are shown.

C) 3D digital perspective of the physiographic regions within the study area, looking north-west. Faults (after Forsyth, 2001) are shown. See A (previous page) for legend.

Table 2.4

Defining features of physiographic regions in the study area. Mean slope values derived from randomised sample (n = 500 for each region) of grid derived from 25 m DEM. F = 158, Sig. = 0.000.

Physiographic Region	Defining Features	Mean Slope (°)
Steep Gullies in Schist	Heavily gullied semischist, with broad flat areas corresponding to the former erosion surface of the Late-Cretaceous Peneplain.	7
Loess-Mantled Dissected Hill Country	Heavily dissected Lower-Tertiary non-marine & marine sediments with loess in some places.	8
Mesas & Buttes	Structural landforms with hard limestone cap rocks & associated scarp slopes.	8
Dissected High-Level Terraces	Dissected and loess-mantled (patchy) terraces forming plateaux underlain by Pleistocene greywacke alluvium.	2
Alluvial Plains (Tertiary Sediments)	Valley fill deposits with alluvium sourced from Tertiary sediments.	4
Alluvial Plains (Quaternary Greywacke Alluvium)	Low-relief floodplain of the Waitaki River and fans on downlands margin.	3

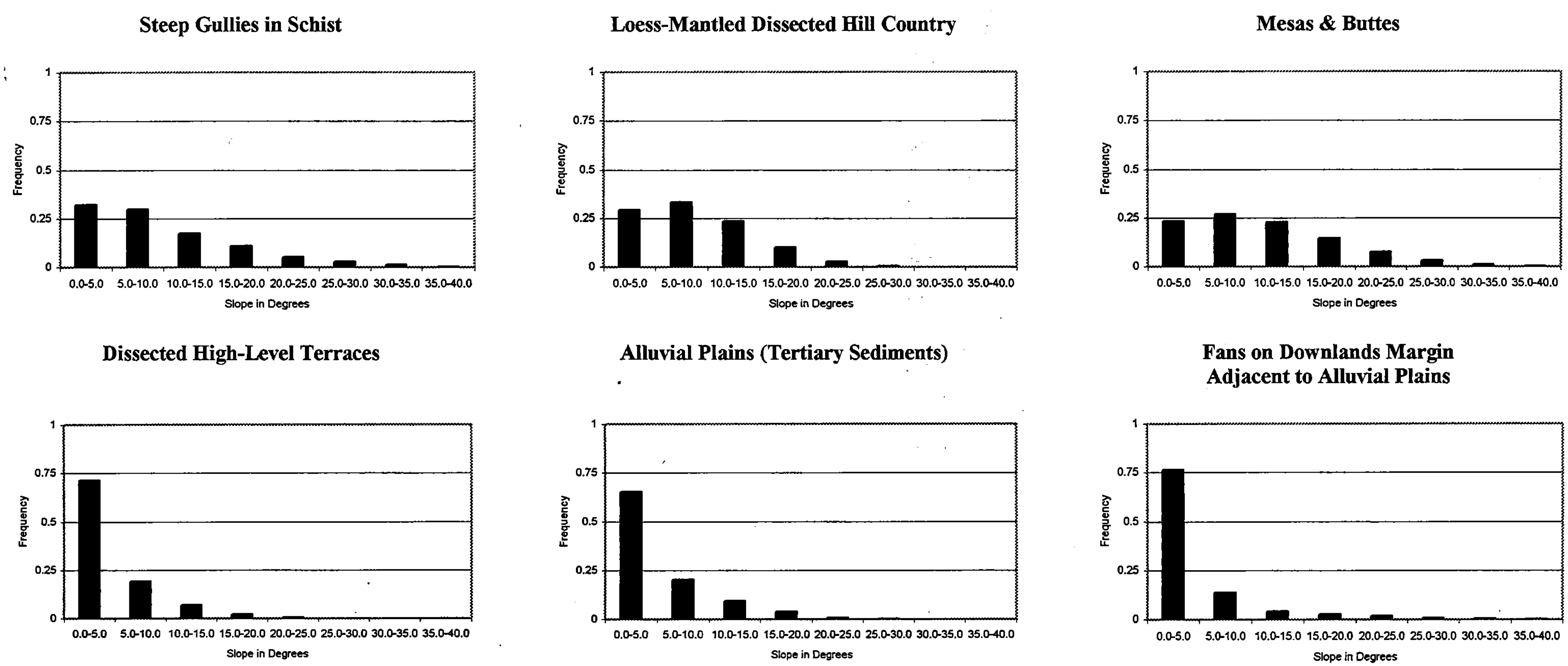


Figure 2.24

Slope class distributions (derived from a 25 m DEM) for physiographic regions in the study area.

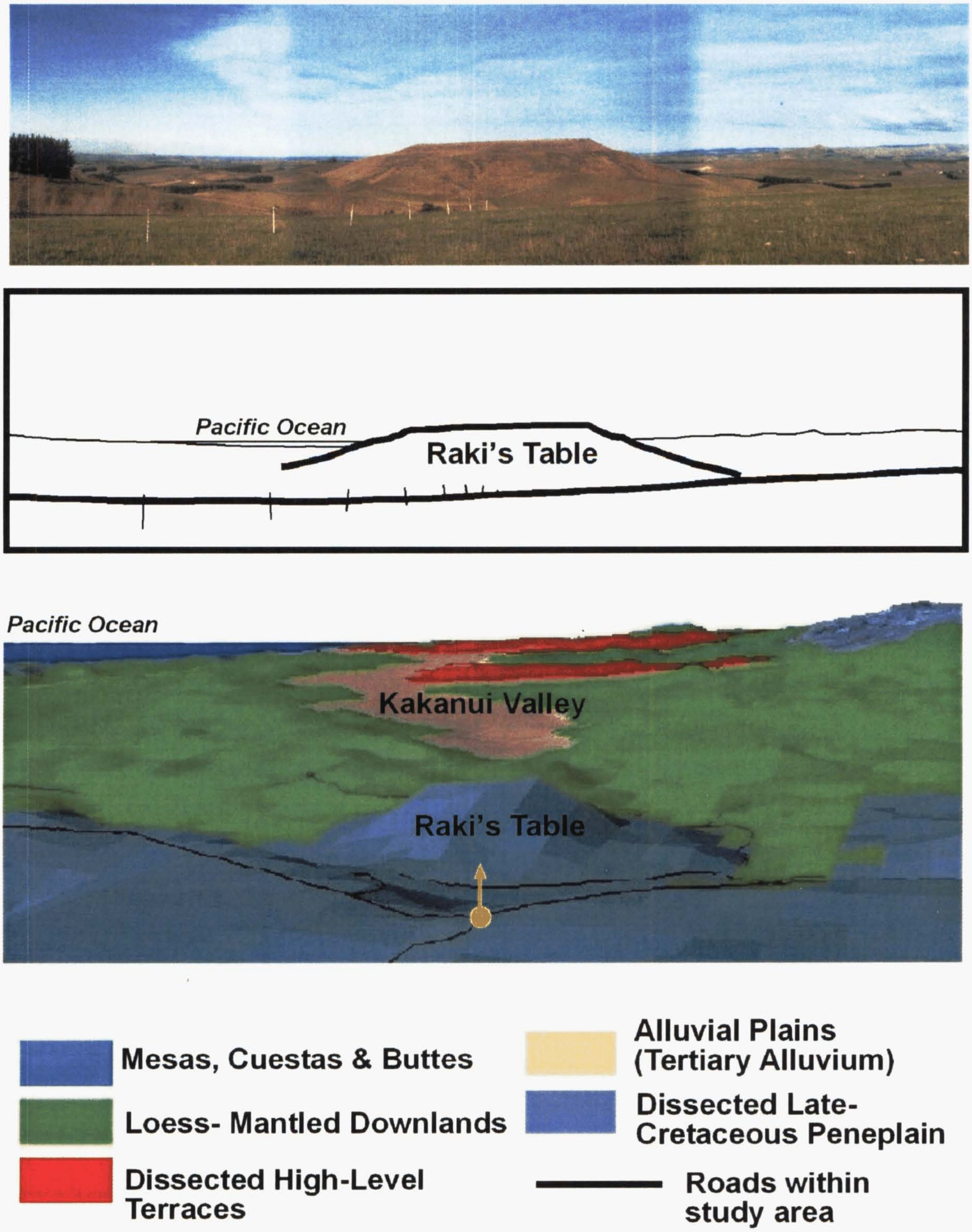


Figure 2.25

Top : Panoramic view (centred S) of Raki's Table, a mesa characteristic of the Mesas, Cuestas and Buttes physiographic region within the study area.

Centre: Schematic of the panoramic view of Raki's Table.

Bottom: 3D digital perspective (based on a 25 m DEM) of the physiographic regions shown above, with the location and orientation of the camera indicated (yellow). Note the "smoothing" that occurs when the actual landscape is modelled with the DEM.

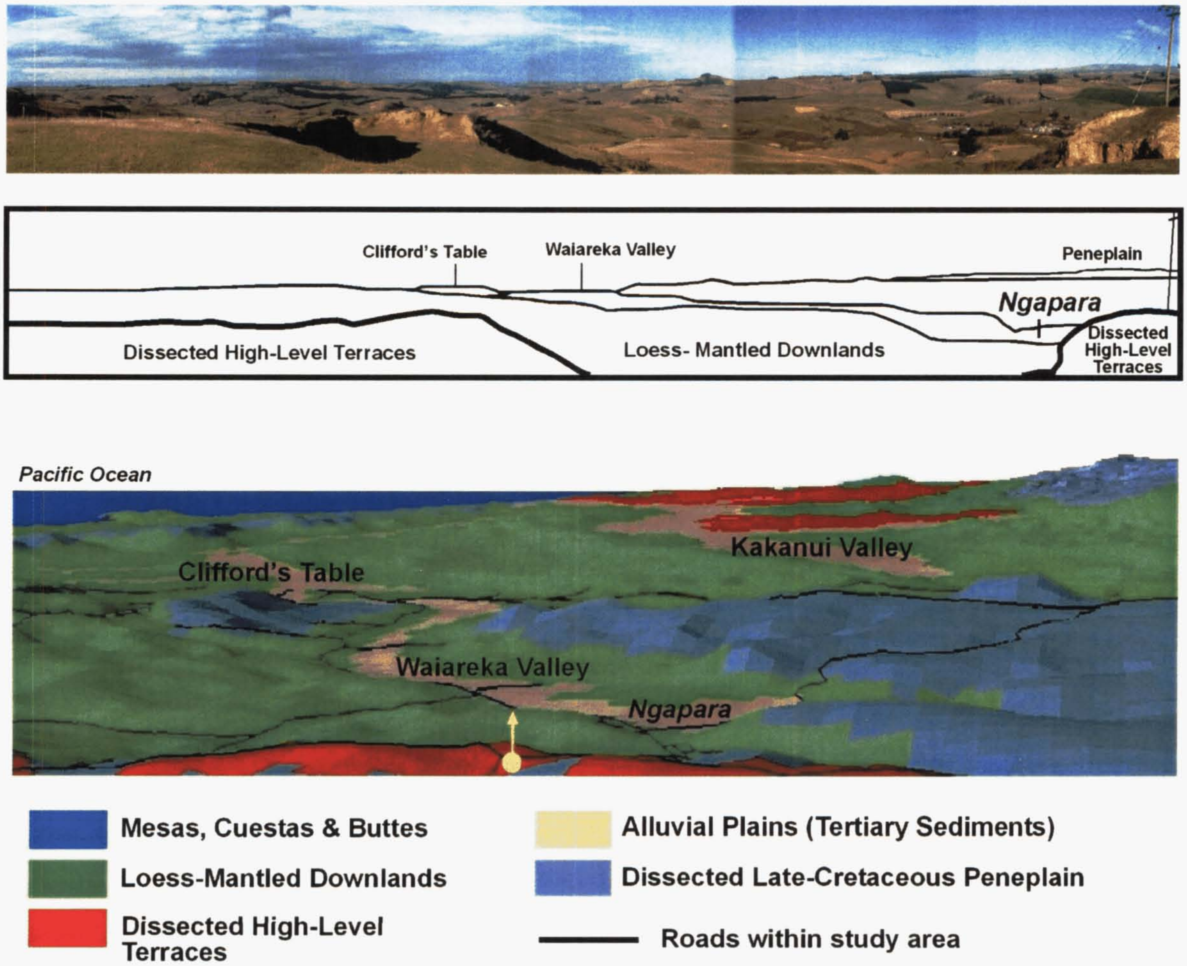


Figure 2.26

Top : Panoramic view (centred SE) looking down the Waiareka Valley.

Centre: Schematic of the panoramic view looking down the Waiareka Valley.

Bottom: 3D digital perspective (based on a 25 m DEM) of the physiographic regions shown above, with the location and orientation of the camera indicated (yellow). Note the "smoothing" that occurs when the actual landscape is modelled with the DEM.

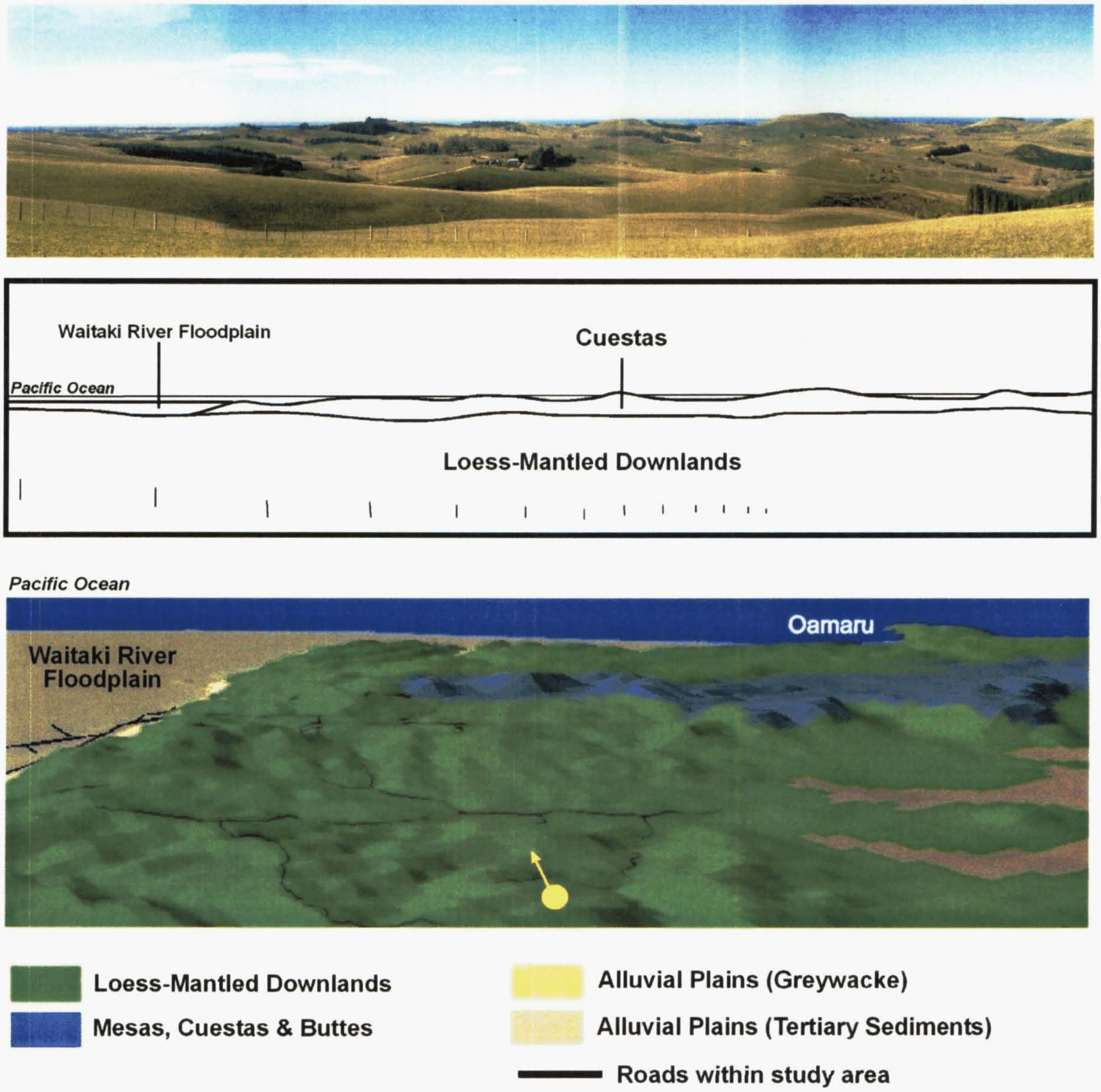


Figure 2.27

Top : Panoramic view (centred E) of the Loess-Mantled Downlands and Cuestas in the eastern part of the study area, with the Waitaki River floodplain in the distance.

Centre: Schematic of the panoramic view of the loess-mantled downlands looking east.

Bottom: 3D digital perspective (based on a 25 m DEM) of the physiographic regions shown above, with the location and orientation of the camera indicated (yellow). Note the "smoothing" that occurs when the actual landscape is modelled with the DEM.

2.7 Soil Taxa

Three major soil surveys of differing scales cover the study area, and date from the late 1960s to the early 1970s (Figure 2.28).

The smallest-scale survey is that of Soil Bureau Staff (1968), in their General Survey of the Soils of South Island, New Zealand. The General Survey was carried out to give an overall picture of South Island soil pattern and to provide basic information for predicting future land use and broad fertility needs. Due to the small scale of the maps produced from the general survey (1:253,440), the SMUs used are necessarily broad, and are useful mainly in showing the distribution and extent of the main kinds of soils (Soil Bureau Staff, 1968). The maps were also claimed to be useful as a basis for preparing single factor maps (*e.g.* depicting stony soils, soils with high P requirements, soils suitable for market gardens *etc.*). The mapping units were soil sets, ten of which occur within the extent of the study area (Figure 2.28).

The next largest scale soil survey of North Otago is that of Kear *et al.* (1967). This was part of a wider survey of the downs and plains of Canterbury and North Otago, with an emphasis on soils on pastoral and cropping land. The aim of the survey was to separate soil units as precisely as the map scale allowed and to describe the soil limitations (Kear, 1967). The limitations of scale (1:126,720), as with the General Survey, meant that the soil series-based SMUs were broad and only the main areas of soil types, but not all small areas, were mapped. Eleven mapped soil series fall within the extent of the study area (Figure 2.28).

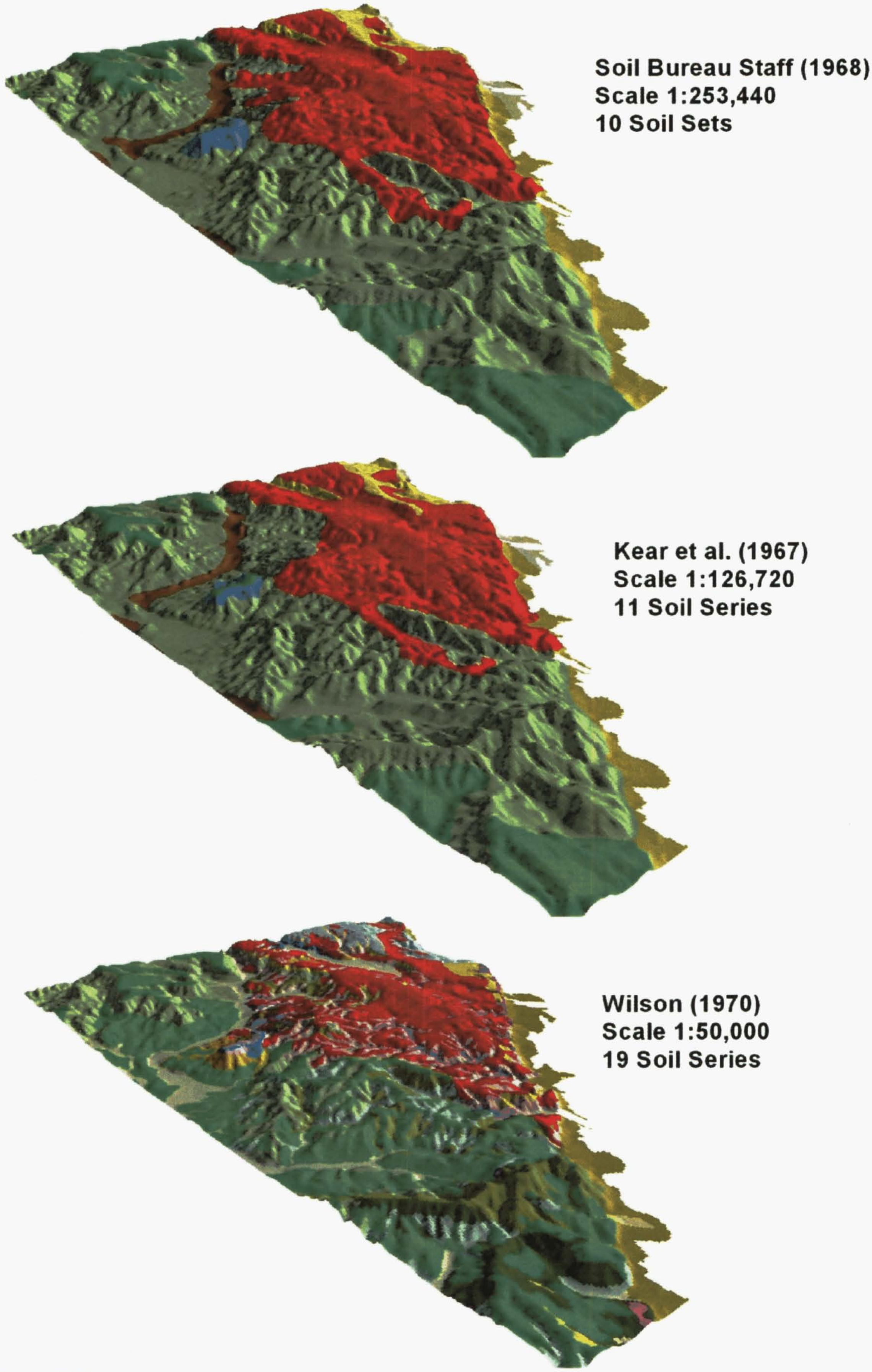


Figure 2.28

Comparison between existing soil maps covering the study area (represented here as 3D digital perspectives, looking north-west) of the number of SMUs at different mapping scales.

The largest-scale, highest-resolution soil survey for North Otago is that of Wilson (1970), mapped at scale 1:50,000 (Figure 2.28). This scale is typical of regional land use planning surveys (Dent, 1981), and Wilson's (1970) report emphasised the suitability of series for agricultural and horticultural production, including assessments of soil drainage and water-holding capacity. Nineteen soil series were mapped within the extent of the study area.

Although the number of individual SMUs able to be delineated increases with increasing scale, it is not possible to definitively relate this to increasing resolution. Resolution depends on the number of observations and the grain of the soil pattern (McBratney, 1998). While sampling densities for 1:253,440-, 1:126,720- and 1:50,000-scale surveys are generally in the order of 1 per 13.5 km^2, 1 per 2 km^2 and 1 per 50 ha, respectively (Dent, 1981), this information has not been explicitly provided for the maps of Soil Bureau Staff (1968), Kear *et al.* (1967) and Wilson (1970). The increase in scale from 1:253,440 to 1:126,720 does not appear to materially increase the resolution of soil pattern and number of mapping units, but the increase in scale from 1:126,720 to 1:50,000 does (Figure 2.28). This suggests that the higher sampling density of Wilson's (1970) survey is better capturing the grain of the soil pattern and attendant variations in pedon morphology.

New Zealand Soil Classification Orders (Hewitt, 1998) within the study area inferred from the New Zealand Genetic Classification (NZGC) designations of Soil Bureau Staff (1968), Kear *et al.* (1967) and Wilson (1970) show that Pallic Soils dominate the area, as expected from the extensive occurrence of loess parent materials and the climate characteristics (Section 2.5.2). With increasing scale the delineated boundaries of these Pallic Soils are better resolved, as is the spatial extent of Melanic Soils occurring on marls and limestones and Recent Soils on valley-fill alluvium.

Wilson's (1970) map is used in the present work for the development of a quantitative SLM of the study area (see Section 3.1 and Chapter 4) because it provides the highest resolution spatial data. Figure 2.29 is adapted from that part of Wilson's (1970) map that falls within the study area, and the legend is organised according to the physiographic regions shown in Figure 2.23. In Wilson's (1970) original map, individual soil phases within soil series were used as SMUs (*e.g.* Ngapara Series, fine sandy loam rolling phase; Ngapara Series, mottled fine sandy loam phase). For brevity, and to simplify the quantitative SLM analysis presented in Chapter 4, all soil phases have been aggregated to form SMUs based on soil series alone.

Table 2.5 presents definitions for each soil series from Wilson (1970), and from Soil Bureau Staff where the relevant definitions are absent from Wilson's (1970) report. Most of these definitions are accepted for the present work, and where necessary have they been amended according to their use in fieldwork for this study and the development of quantitative SLMs. Representative pedons of the most spatially extensive soils - those used in the development of the quantitative SLMs presented in Chapters 4 and 5 - are described in Appendix 2.

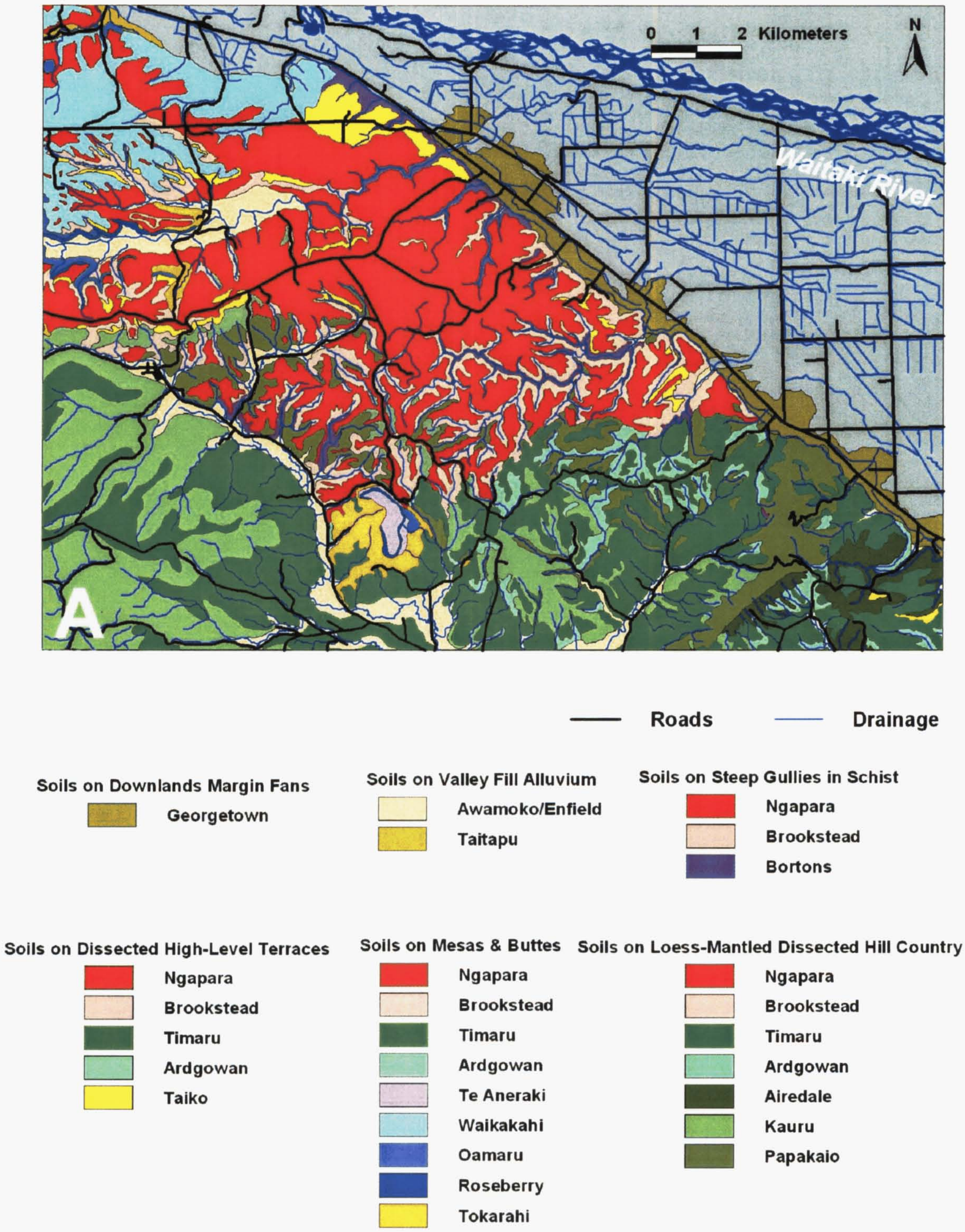


Figure 2.29

A) Soil series in the study area. Adapted from Wilson (1970), originally mapped at scale 1:50,000.

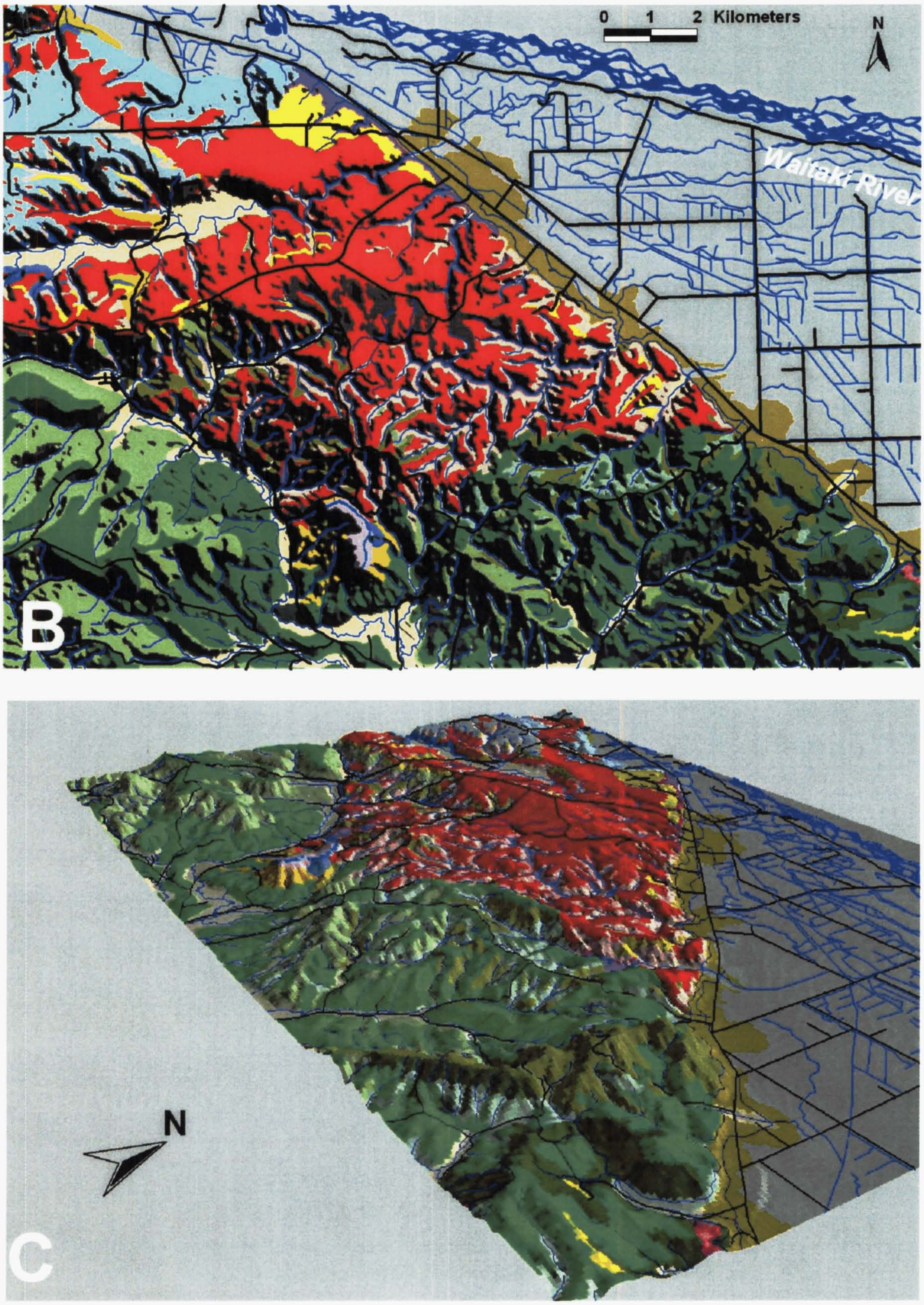


Figure 2.29 continued

B) Soil series in the study area, overlain by a shaded digital relief model. Adapted from Wilson (1970), originally mapped at scale 1:50,000. See A (previous page) for legend.

C) 3D digital perspective of the soil series in the study area. Adapted from Wilson (1970), originally mapped at scale 1:50,000. See A (previous page) for legend.

Table 2.5

Soil series in the study area as defined by Wilson (1970, with NZGC terminology retained) and Soil Bureau Staff (1968), with amendments for the present work. See Appendix 2 for soil profile descriptions and NZSC classifications obtained in the field for the present work.

	Soil Series	Definition **W – Wilson, 1970** **S – Soil Bureau Staff, 1968** **A – Amendments used in this study**
Soils on Downlands Margin Fans	**Georgetown**	W – Fragic Yellow-Grey Earths derived from shallow loess overlying rewashed loess & Tertiary sediments alluvium on alluvial fans.
Soils on Valley Fill Alluvium	**Awamoko**	W – Recent soils derived from Tertiary Sediment alluvium & rewashed loess. A – Presence of aggrading & composite Recent soils on floodplains.
	Enfield	W – Incipient fragic Yellow-Grey Earths derived from rewashed loess & occurring on low terraces above stream floodplains.
	Taitapu (variant)	S – Gley Recent soils derived from greywacke & schist alluvium. A – Some limestone colluvium derived from nearby exposures.
Soils on Dissected High-Level Terraces	**Ngapara**	W – Weakly clay illuvial, fragic Yellow-Grey Earths derived from coarse-textured quartzofeldspathic loess. A – Loess thickness >1.5 m.
	Brookstead	W – Incipient fragic Yellow-Grey Earths derived from coarse-textured colluvial loess, occurring on moderately steep to steep gully slopes. A – Loess thickness >1.5 m, also greywacke & limestone colluvium within colluvial loess.
	Timaru	W – Weakly clay illuvial, fragic Yellow-Grey Earths derived from fine-textured, quartzofeldspathic loess. A – Loess thickness >1.5 m.
	Ardgowan	W – Incipient fragic Yellow-Grey Earths derived from fine-textured colluvial loess, occurring on moderately steep to steep gully slopes. A – Loess thickness >1.5 m, also greywacke & limestone colluvium within colluvial loess.
	Taiko	W – Yellow-Grey Earths derived from shallow loess over weathered greywacke gravels and loess/greywacke colluvium. Occur mainly on moderately steep to steep gully slopes. A – Also occur on flatter High Terrace surfaces. Loess mantle <1 m.

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Table 2.5 continued

	Soil Series	Definition W – Wilson, 1970 S – Soil Bureau Staff, 1968 A – Amendments used in this study
Soils on Steep Gullies in Schist	**Ngapara**	See above
	Brookstead	See above
	Bortons	**W** – Steepland soils associated with Yellow-Grey Earths, derived from schist & loess/schist colluvium. **A** – Also present on flatter surfaces – thin loess on schist bedrock.
Soils on Mesas & Buttes	**Ngapara**	See above
	Brookstead	See above
	Timaru	See above
	Ardgowan	See above
	Te Aneraki	**W** – Carbonate accumulative Brown Granular Clays derived from calcareous tuffs & tuffaceous limestone, occurring on escarpment dipslopes & lower scarp faces. **A** – Calcareous tuffs & tuffaceous limestones are not mapped in the study area by Gage (1957) & were not observed by the author. Te Aneraki Soils do not seem to occur in the study area as mapped by Wilson (1970).
	Waikakahi	**S** – Rendzinas & associated soils derived from shallow loess over limestones & marls.
	Oamaru	**W** – Rendzinas derived from hard, massive limestone.
	Roseberry	**W** – Steepland soils associated with Rendzinas, derived from limestone on steep & very steep upper scarp face slopes. **A** – Steepland soils derived from limestone colluvium, with incorporation of some glauconitic sediments, possibly with limestone residuum.
	Tokarahi	**W** – Weakly clay illuvial Yellow-Grey Earths derived from loess overlying glauconitic sandstones & greensands. **A** – Clay-rich Melanic Soils derived from glauconitic sandstones & greensands.

Continued overleaf

Table 2.5 continued

	Soil Series	Definition **W – Wilson, 1970** **S – Soil Bureau Staff, 1968** **A – Amendments used in this study**
Soils on Loess-Mantled Dissected Hill Country	**Ngapara**	See above
	Brookstead	See above
	Timaru	See above
	Ardgowan	See above
	Airedale	W – Weakly clay illuvial Yellow-Grey Earths derived from shallow loess overlying weathered siltstone.
	Kauru	W – Weakly clay illuvial Yellow-Grey Earths derived from shallow loess overlying sandstone.
	Papakaio	W – Yellow-Grey Earths derived from shallow loess overlying quartz gravels & quartz conglomerates. A – Loess sometimes absent – A/R or A/C profile.

As discussed in Section 2.5, the soil pattern in controlled by the spatial occurrence of geological and loessial parent materials. These parent materials largely determine pedon morphology and ascribed soil series, and their physical and chemical nature also has a significant influence on soil properties. The geological parent materials can be classified as those that are base rich, quarztofeldpathic, siliceous, and colluvial/alluvial admixtures of these.

Base rich parent materials are comprised of calcareous sediments (marls and limestones) and glauconitic/calcareous sediments. The Otekaike Limestone is composed of up to 96% $CaCO_3$ with trace amounts of Fe_2O_3, MgO and P_2O_5 (Park, 1918, cited by Gage, 1957), and is the parent material of the well-structured, high-nutrient status Waikakahi Soils (see Appendix 2). Loess accumulation on the Otekaike Limestone parent material is more evident in the Waikakahi Soils, yet this loess has been incorporated into these soils' characteristically well-structured subsoils, and the accumulation of nutrient-poor quartzofelsdpathic loess has been more than compensated for by the high base status of the underlying limestone. Where loess is absent on these calcareous sediments, highly fertile, well-structured topsoils form directly into bedrock with a clear lithic contact (Oamaru

Soils, see Appendix 2), and on steeper slopes and colluvial material Roseberry Soils occur (see Appendix 2). Glauconitic/calcareous sediments are comprised of glauconitic sandstones and greensands. The relatively high levels of Fe, Mg, K, Ca and Na within the glauconitic sediments contribute to the naturally high nutrient status and good topsoil structure of the Tokarahi Soils (see Appendix 2). Wilson (1970) mapped Te Aneraki Soils (Figure 2.29) formed in mafic/calcareous parent materials, but these calcareous tuffs were not observed during the course of this study (see Section 3.1).

Quartzofeldspathic geological parent materials are comprised of the semischist of the Kakanui Metamorphic Group and the greywacke gravels of the High Terraces, with their contribution to inherent nutrient status probably being similar. In addition to the nearly 60% silica composition of the semischist, minor amounts of FeO and Fe_2O_3 (7% combined), CaO (4%), K_2O (3%), MgO (2%) and Na_2O (2%) and trace amounts of MnO (0.2%) have been measured (Park, cited by Gage, 1957).

Siliceous parent materials are comprised of the quartzose gravels of the Papakaio Formation and the quartzose/kaolinitic sandstone and siltstone members within the Kauru Formation. These geological parent materials are poor in nutrient elements, and outcrop over much of the study area comprising the highly dissected hill country. The local soil series are defined by the following lithologies and the overlying thickness of loess:

- Thin (0-1 m) loess over quartzose gravels (Papakaio Soils)
- Thin (0-1 m) loess over sandstones (Kauru Soils)
- Thin (0-1 m) loess over siltstones (Airedale Soils)

These soils tend to be poorly structured and of low nutrient status, due to the low clay, Fe oxide and base cation content of the parent materials.

Colluvial material and alluvium in the Awamoko and Waiareka Valleys is derived from Tertiary sediments and constitutes the geological parent materials for Awamoko and Enfield Soils, the latter having a mantle of thin loess. Although the alluvium is sourced from both high- and low-nutrient element lithologies, the chemical nature of the pedons present might be expected to show a degree of homogeneity due to mixing occurring in the fluvial system. The Georgetown soils of the downlands margin are derived from alluvium and colluvium derived from both Tertiary sediments and semischists, as well as both primary and colluvial/slopewashed loess.

To summarise, the lithological units in the study area determine the spatial distribution and extent of differing parent materials, with important differences in inherent physical and chemical properties. A description and discussion of A Horizon % C and % N analysis for soils on different parent materials is presented in Chapter 6.

The map in Figure 2.29 is the clearest spatial representation of Wilson's (1970) pedological research. In addition to the map itself, Wilson (1970) provided explicit conceptual diagrammatic models describing the landscape position of soil series and their parent materials. These are shown in Figure 2.30, with Wilson's (1970) original landform designations retained. Soils on valley alluvium (Awamoko, Enfield, Uxbridge and Taitapu Series) and the downlands margin (Georgetown Series) are not included. For these SLMs of the Dissected High Downlands Terraces, the Dissected Hill Lands and the Dissected Limestone Tablelands, it is clear that the soil-landscape pattern is determined by the spatial occurrence and thickness of primary and colluvial/slopewashed loess parent materials over the underlying geology. Soil series are defined by these geological units where loess is absent or thin (<1 m), and are defined by the nature of loess parent materials where loess thickness exceeds 1.5 m. The SLM for the Escarpments and Mesas is included primarily to illustrate the mesa landform occurring in the study area (also see Section 2.6, Figure 2.25) with Oamaru and Roseberry Soils occurring on the resistant limestone cap rock. The igneous parent materials and cuesta landforms are not characteristic of the study area.

Although Wilson's (1970) SLMs (Figure 2.30) graphically capture the pedologist's mental picture of the soil-landscape, and succinctly present this mental picture for the reader, they are in themselves impossible to test or verify because Wilson (1970) left no record of the exact spatial locations of the individual soil series observations that were used to construct the models. More seriously, Wilson (1970) presented no explicit rules to identify the land components to which soils are associated. The soil map itself is the only model that can be tested in any spatially quantitative sense for its SMUs are located with respect to, and can be sampled using New Zealand Map Grid coordinates. The investigation of the contents of Wilson's (1970) SMUs is described in Section 3.1.

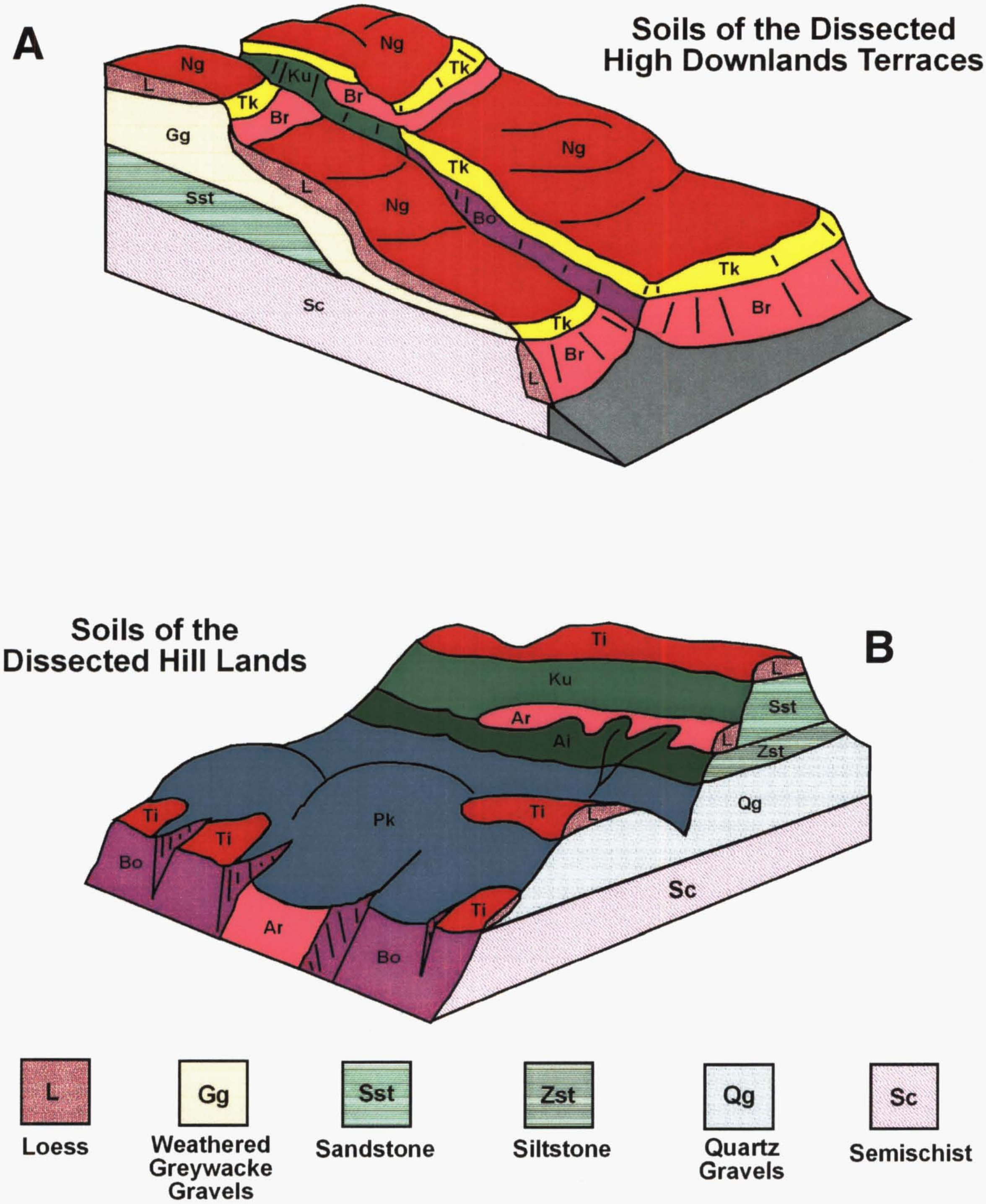


Figure 2.30

Diagrammatic Soil-Landscape Models for the study area, adapted from Wilson (1970). A) Soils of the dissected high downlands terraces. Ng = Ngapara; Br = Brookstead; Tk = Taiko; Ku = Kauru; Bo = Bortons. B) Soils of the dissected hill lands. Ti = Timaru; Ar = Ardgowan; Ku = Kauru; Ai = Airedale; Pk = Papakaio; Bo = Bortons.

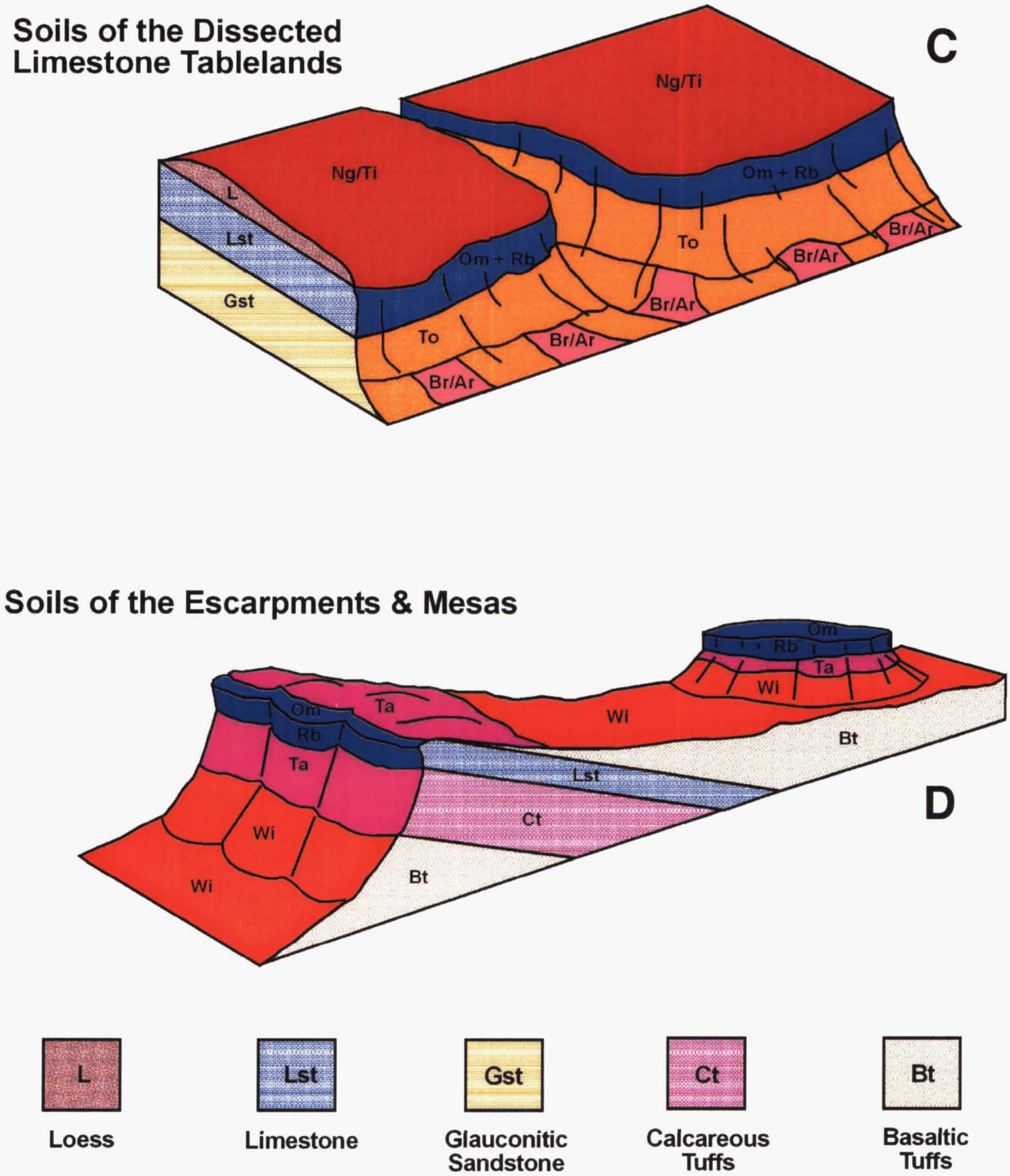


Figure 2.30 continued

C) Soils of the dissected limestone tablelands. Ng/Ti = Ngapara/Timaru; Om + Rb = Oamaru & Roseberry; To = Tokarahi; Br/Ar = Brookstead/Ardgowan. D) Soils of the escarpments and mesas. Om = Oamaru; Rb = Roseberry; Ta = Te Aneraki; Wi = Waiareka.

Chapter 3

Data For Quantitative Soil-Landscape Modelling

3.1 Soil Data

As discussed in Section 2.7, Wilson's (1970) soil map (Figure 2.29) provides the largest-scale, highest-resolution data available for the study area, and for this reason it was used in the development of qSLM 1 (see Chapter 4). Presented below is a description of the procedures conventionally used for soil survey at the time, the transformation of the map into digital form, an assessment of the purity of Wilson's (1970) SMUs, and a critical analysis of the suitability of this map for inclusion in GIS-based soil-landscape modelling.

3.1.1 Wilson's (1970) Soil Map

Figure 3.1 outlines the general methodology used for the construction of Wilson's (1970) map. Figures 3.1a and 3.1b simulate the use of stereoscopic analysis in the conventional (as opposed to digital) terrain analysis of the area in an attempt to subdivide the landscape into distinct landform components and potential soil-landscape units (SLUs). Wilson (1970) delineated SLU boundaries primarily on the basis of significant breaks in slope that were evident in stereoscopic analysis (Figure 3.1). The product of this initial step was a template for potential SLUs that were retained or discarded after field sampling and description. Wilson (1970) did not provide details on the locations and density of his observations, but most conventional 1:50,000 soil surveys have an average density of one observation per 50 ha (Dent and Young, 1981).

Wilson's (1970) soil survey produced a database of soil taxonomic units (STUs) from field descriptions of pedons, and qualitative diagrammatic SLMs of the area were developed (see Figure 2.30, Section 2.7). Delineated soil bodies were defined on the basis of the SLUs and the SLMs. SMUs were phases of soil series based on texture, drainage status and landscape position (Figure 3.1c). Wilson's (1970) final map was presented on an orthographically corrected black and white aerial photomosaic.

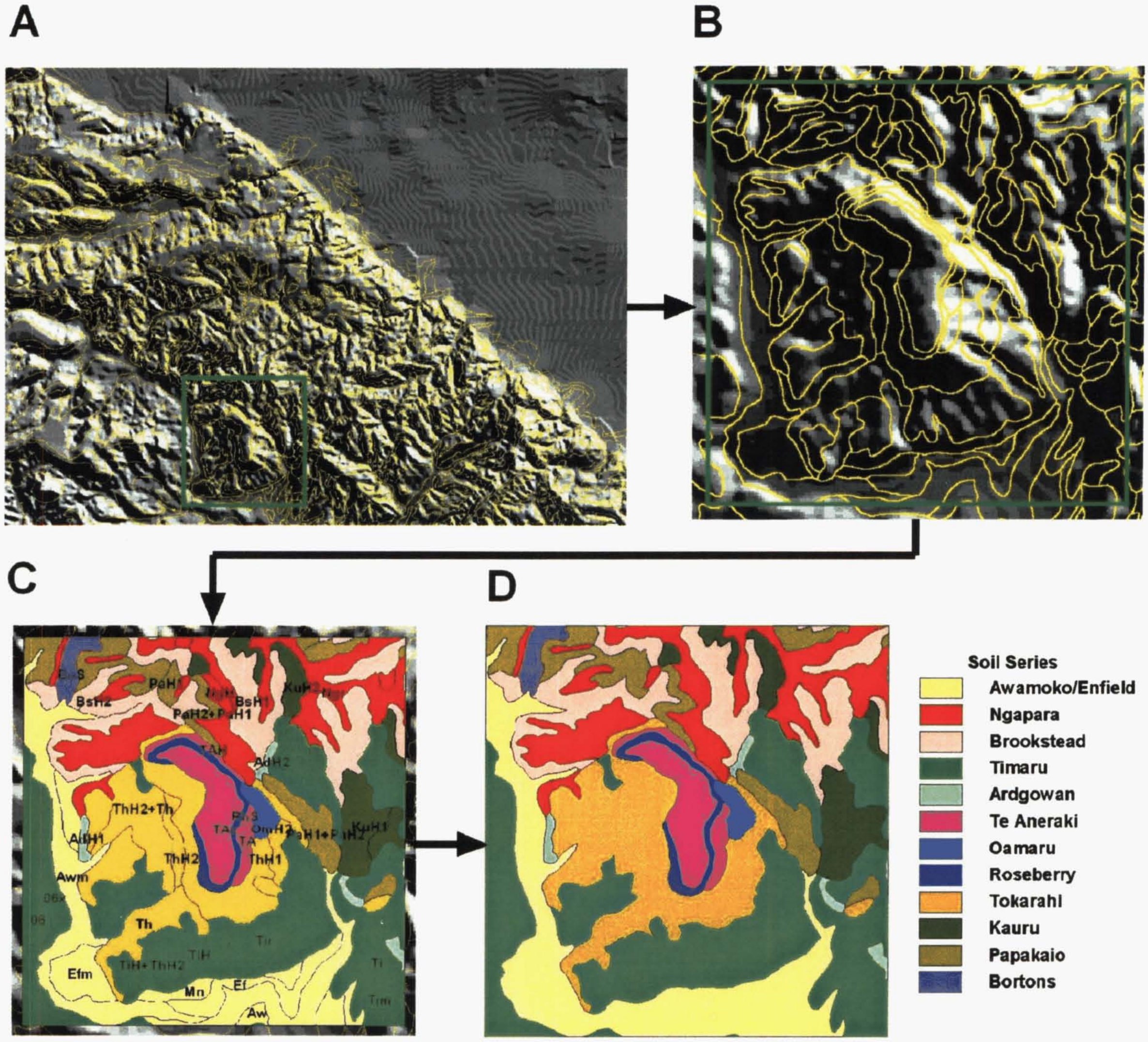


Figure 3.1

The methodology used for Wilson's (1970) soil map construction. A) and B) SLUs (yellow) interpreted from stereoscopic analysis of aerial photographs (represented here by a digital shaded relief model). C) SLUs transformed into SMUs of soil phases based upon soil survey. D) The amalgamation of Wilson's (1970) soil phase-based SMUs into the soil series-based SMUs used in the present work.

The version of Wilson's (1970) map used here is a spatially registered digitised copy of the original hardcopy map. The digitising process was automated (T. Webb, pers. comm.), which might have reduced errors associated with manual digitising (Bolstad *et al.*, 1990), but introduced 'sliver' polygon errors that required editing. While the general sources of error in Wilson's (1970) map and its transformation into a digital database are recognised, it is beyond the brief of the present work to develop a systematic quantitative model of error propagation and its effect on spatial analysis such as that described by Heuvelink (1998). The quantification of propagated errors is recommended for future research.

As stated in Section 2.7, for brevity and to simplify the quantitative SLM analysis presented in Chapter 4, soil phases were generalised to soil series (Figure 3.1d). The purity of Wilson's (1970) series-based SMUs was assessed by a field sampling programme. ArcView 3.1 software (ESRI, 1996) was used to intersect randomly generated NZMG points with Wilson's (1970) SMUs so that 10 points fell within each SMU (Figure 3.2a). A Trimble ProXR 12-channel GPS antenna and receiver (Trimble, 2002) was used for field navigation to these points. The slope position of the point was noted, and slope and aspect were measured using compass and clinometer. Soils were investigated by hand auger up to 2 m depth, and horizon thicknesses, root depth, colour, textures and moist and wet consistence were described. Sampled pedons were allocated to soil series on the basis of existing series definitions. The spatial locations of sample points were recorded with the ProXR GPS unit, and later differentially corrected by post processing to sub-5 m accuracy for use in qSLM 2 (Chapter 5). Topsoils at all locations were sampled for C and N analysis (Chapter 6).

Type sections of pedons are presented in Appendix 2, and descriptions of sample point pedons are shown in Appendix 3. The mean percentage agreement between SMUs and observed STUs was 54%, with agreement ranging from non-existent (0%) to complete (100%) among SMUs (Table 3.1).

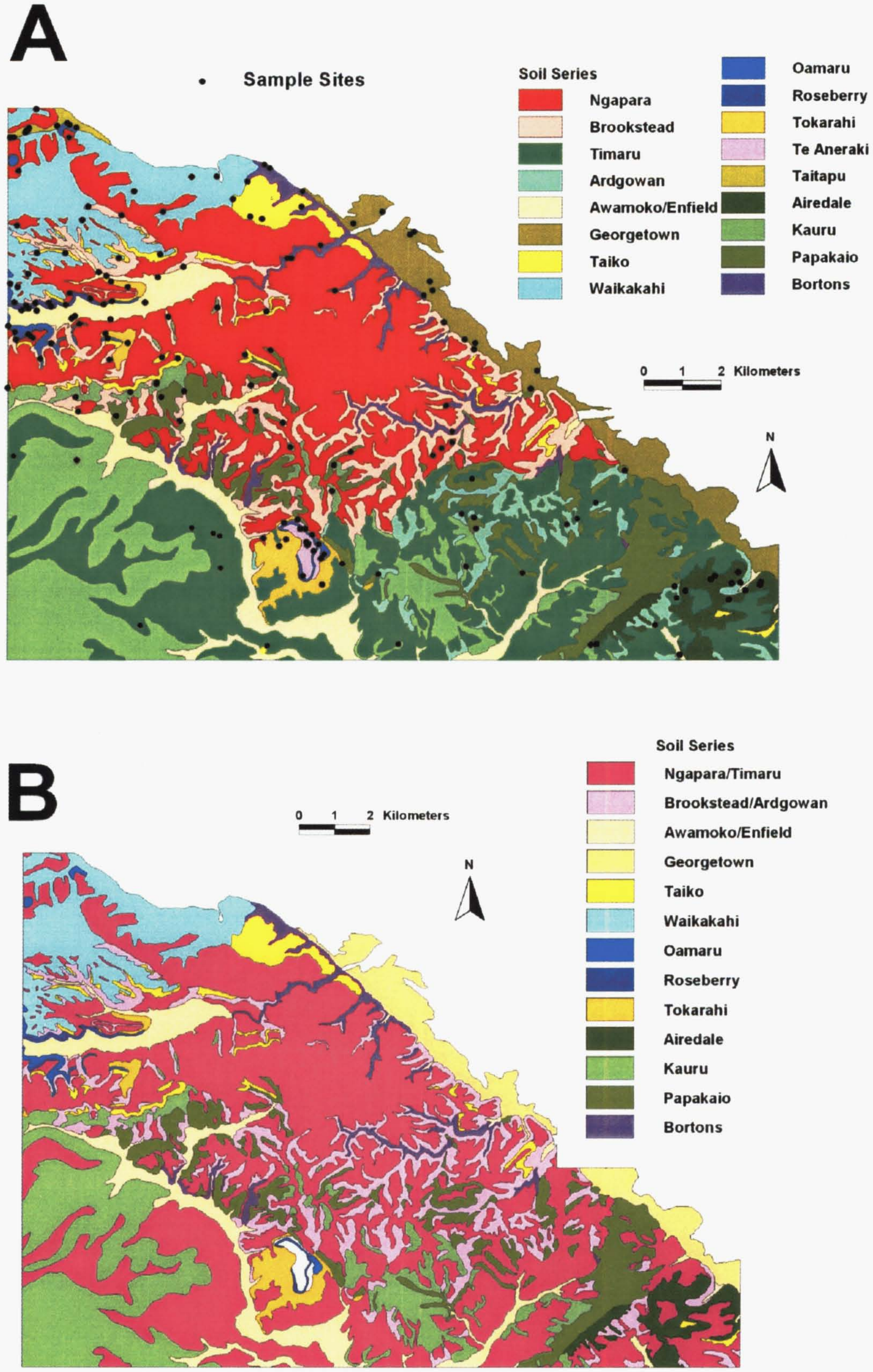


Figure 3.2

A) Wilson's (1970) SMUs within the study area, with locations of sample points visited during fieldwork.

B) SMUs within the study area used for the development of qSLM 1 (Chapter 4).

From Wilson (1970).

Table 3.1

Percentage agreement between STUs observed in the field and taxa predicted from Wilson's (1970) SMUs.

Corresponding SMU Taxa		Observed STUs: Ng	Ti	Br	Ar	Aw/Ef	Ge	Tk	Wk	Om	Rb	Tt	TA	To	Ai	Ku	Pk	Bo	N	SMU Purity (%)
Ngapara	Ng	8		1				1									1	1	12	67
Timaru	Ti	1	2											6			1		10	20
Brookstead	Br	2		7												1			10	70
Ardgowan	Ar		3		5												2		10	50
Awamoko/Enfield	Aw/Ef	2		1		7													10	70
Georgetown	Ge						10												10	100
Taiko	Tk	1						7										1	9	78
Waikakahi	Wk	6					1	2	2										11	18
Oamaru	Om	3							2	1	1	1		4					12	8
Roseberry	Rb									1	6			4					11	55
Taitapu	Tt								1			9							10	90
Te Aneraki	TA										1		0	9					10	0
Tokarahi	To			2							1			8					10	80
Airedale	Ai		1		1			2							6				10	60
Kauru	Ku	1	1	1				2						2	1	2	1		11	18
Papakaio	Pk	2		1				1								1	5		10	50
Bortons	Bo			1				1										8	10	80
N		*n=26*	*n=7*	*n=14*	*n=6*	*n=7*	*n=11*	*n=16*	*n=5*	*n=2*	*n=8*	*n=10*	*n=0*	*n=33*	*n=7*	*n=4*	*n=10*	*n=10*		
SMU Predictive Success (%)		31	29	50	83	100	100	44	40	50	75	90	0	24	86	50	50	80		

The percentage agreement between STUs predicted from the map and STUs identified in the field is a measure of the purity of Wilson's (1970) map units. A purity of at least 85% has in the past been specified as a minimum level of purity allowable for simple SMUs (*e.g.* Taylor and Pohlen, 1970), but was often specified without guidance as to how this optimistic value was to be achieved or checked (Dent and Young, 1981), and has been criticised for being an unattainable limit of mapping accuracy (Adams and Wilde, 1980). While it is clear from Table 3.1 that the purity of two of Wilson's (1970) individual soil series-based SMUs exceeded this 85% value (Taitapu and Georgetown Series) and that three others approached it (Taiko, Tokarahi and Bortons Series), many fell below this level and the overall purity of SMUs was 51%. Acknowledging the small sample sizes (Table 3.1), this mean purity supports the contention of Adams and Wilde (1980) that a purity of ~50% is probable in most mapping units at the series (or phase) level in New Zealand.

The nature of STU impurities highlights the limitations of Wilson's SMUs. An extreme example is that of Te Aneraki Soils (0% purity), where the putative parent material (tuffaceous limestone) had in fact not been mapped (Gage, 1957) and was not observed in the field in the course of fieldwork for the present study. The impurities within most other SMUs reflect the presence of different geological parent materials to those expected according to Gage's (1957) map. Because Tokarahi Soils constitute approximately 30% of impurities within Oamaru and Roseberry SMUs, 60% of impurities within Timaru SMUs and 90% of the Te Aneraki SMUs, Wilson (1970) clearly underestimated the spatial distribution of glauconitic sandstones and greensands as parent materials, which resulted in the low purity of these SMUs. Impurities within SMUs defined by loessial parent materials reflect the limitations of predicting the occurrence and thickness of both primary loess and colluvial/slope-washed loess.

The impurities of Wilson's (1970) SMUs reflect two significant sources of error: boundary errors resulting in the incorrect delineation of SLUs, and SMU grain size (McBratney, 1998) being too coarse to capture the spatial variation occurring at finer scales. The former error is the result of SLU boundaries incorrectly crossing lithological boundaries, as evidenced in the low purity of the Timaru Series SMU. The impurity arises from delineation of SLU boundaries through physiographic analysis without regard to geological boundaries. The latter error reflects the fact that loess distribution and thickness in particular is subject to variation at ranges that cannot be represented on Wilson's (1970) 1:50 000-scale map; the variation is too fine-grained. Boundary errors between lithological units constitute the majority of SMU impurities, while other impurities are due to both errors and problems of resolution in physiographic analysis within individual lithological units (*e.g.* the presence of Waikakahi and Roseberry Series STUs within the Oamaru SMU). The inferred relative contribution of errors to SMU impurity is: Lithological Unit Boundaries > Topographic Variation within Lithological Unit > Loess Distribution.

3.1.2 Critical Analysis of Wilson's (1970) Soil Map for Quantitative Soil-Landscape Modelling

The mean purity of Wilson's (1970) SMUs (54%) reflected variability not unexpected of New Zealand soils (Adams and Wilde, 1980). Impurities were caused by both fundamental mapping errors and the limitations of map scale in resolving fine-grained variability. For present purposes, it should be emphasised that quantitative soil-landscape modelling using Wilson's (1970) map is concerned with predicting the distribution of SMUs as originally mapped, and is not concerned with predicting the soil taxa after which Wilson (1970) named the SMUs. The field assessment of SMU purity was conducted to investigate the worth of predicting those SMUs, taking into account the known impurities.

It was concluded that Wilson's (1970) map could be used for quantitative soil-landscape modelling. This was based on two factors: 1) the mean SMU purity is in accord with other studies of soil map variability and 2) the map is the highest-resolution available for the study area. Despite some SMUs having impurities of a soil with physical and chemical nature very different to that mapped (*e.g.* impurities of Tokarahi Soils within Timaru series SMUs), most map units have an acceptable level of purity. For these SMUs inclusions are not so different as to seriously affect land management, and as such meet the requirements of the consociation as defined and mapped in soil surveys carried out in the USA (Soil Survey Division Staff, 1993). In combination, these two factors emphasise that despite inherent errors characteristic of all maps based on conventional soil survey, Wilson's (1970) map is a valuable source of soil spatial data. While the range of SMU purities suggests that some SMUs are worth mapping more than others, for present purpose all spatially extensive SMUs falling within the study area were included in the development of qSLM 1 (Chapter 4).

The adaptation of Wilson's (1970) map presented in Figure 3.2a was further edited for use in the analysis described in Chapter 4. Soil series that constituted only a very small percentage of the total area were considered unrepresentative and were excluded (*e.g.* Taitapu Series), as were series that by Wilson's (1970) own definitions could not, on the basis of Gage's (1957) geological map, exist in the area *e.g.* Te Aneraki Series which is formed in tuffaceous limestone that is not present in the study area. The remainder of soils were significant spatially. Those SMUs defined by their primary loess parent materials (Ngapara and Timaru Series) were amalgamated, because their textural differences were unable to be modelled using the present methods. The same was done for SMUs defined by their colluvial/slope-washed loess parent materials (Brookstead and Ardgowan Series), for the same reason. The final map used in the development of qSLM 1 (Chapter 4) is shown in Figure 3.2b.

3.2 Geological Data

3.2.1 Gage's (1957) Geological Map

Gage's (1957) geological map was used for developing quantitative SLMs because it was the largest-scale map available and therefore had the highest resolution representation of the distribution of geological parent materials (Section 2.4).

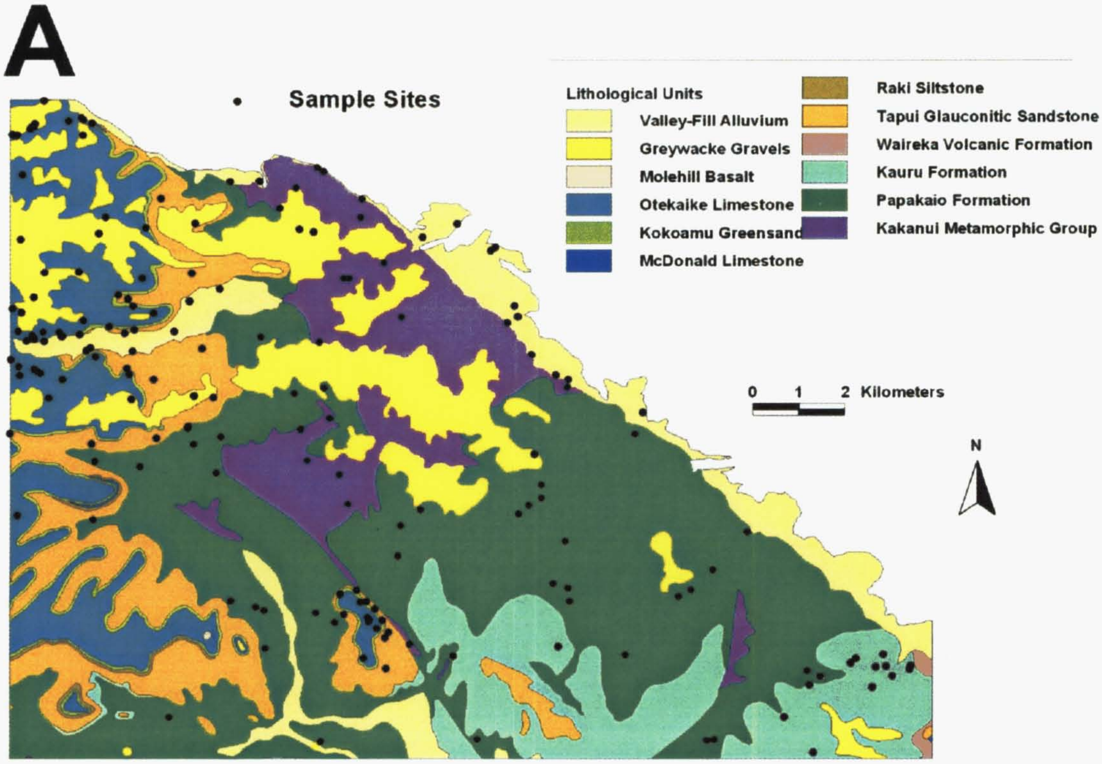
The geological parent material GIS data layer was created from the original hard copy maps in Gage's (1957) Geological Bulletin. Two map sheets covered the study area and when copied, cropped and aligned, it was found that mapped formation boundaries did not consistently match between the two. A "best fit" was made, and the resulting single map was digitally scanned. The digital image was spatially registered and rectified with NZMG points identifiable on both Topomap J41 and the geological map using the Spatial Warp extension in ArcView 3.1 GIS software (ESRI, 1996). The registered and rectified image was then digitised to produce a vector-based data layer, which was subsequently clipped using a polygon defining the maximum extent of the study area.

A range of errors was inevitably associated with the spatial accuracy of Gage's map and its transformation into a digital database. The original geological map was drawn on a topographic basemap of limited detail and low reliability (D. Barrell, pers. comm.), which immediately introduced error into the spatial locations of mapped formation boundaries with respect to the NZMG. Folds and creases in the hard copy map would have introduced distortions in the copying process, and the precision of registration and rectification of the digital copy would have been adversely affected by the inherent errors in locations of identifiable points due the imprecision of the original basemap. Finally, the process of manual digitising introduced positional error in map unit boundaries, although these are likely to be the least significant. Digitised GIS data of high positional quality can be developed when accurate source maps and control data are available (Bolstad *et al.*, 1990), but again this positional quality was compromised in this case by the imprecision of the original basemap.

The general sources of error in Gage's (1957) map data and its transformation into a digital database are recognised, but it is beyond the brief of the present work to develop a systematic quantitative model of error propagation and its effect on spatial analysis such as that described by Heuvelink (1998). Such mathematical descriptions of error propagation are recommended for future work. For the present work the quality of Gage's (1957) map, and the quality of the digitising process, was assessed by ground truthing in the field.

Although fieldwork was not specifically designed to investigate the validity of Gage's (1957) map units, the investigation of Wilson's (1970) SMUs and allocation of pedons to STUs (see previous Section) was often dependent on the recognition of geological parent materials, and as such the soil investigation served as a proxy geological ground truthing exercise.

Figure 3.3a shows the locations of the sample points (N = 176) visited in the course of the soil investigation, presented on Gage's (1957) digitally rendered map. Of these sample points, 123 presented clearly identifiable geological parent materials. The remainder were in thick loess and the underlying geology was not ascertained. Table 3.2 shows the percentage agreement between predicted geological map units at point locations (N = 123) and their corresponding field-identified geological units as defined by Gage (1957), and also shows the percentages of other geological map units in disagreement with those predicted.



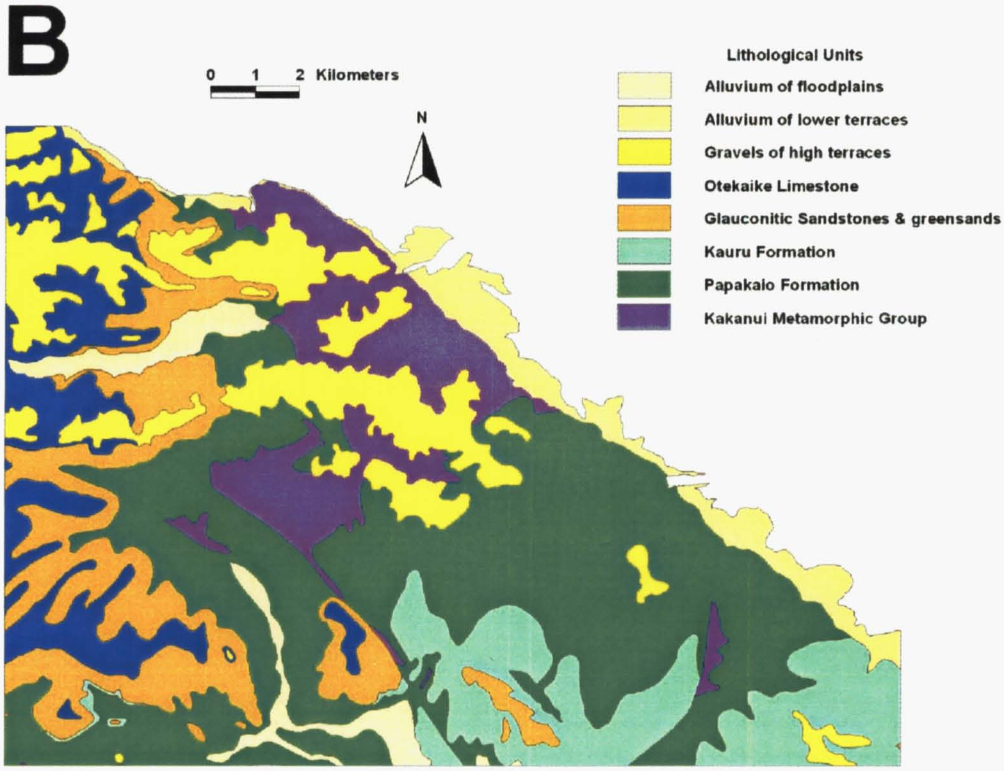


Figure 3.3

A) Lithological units in the study area, adapted from Gage (1957), with locations of sample points visited during fieldwork.

B) Lithological units in the study area used for the development of qSLM 1 (Chapter 4) and qSLM 2 (Chapter 5).

From Gage (1957).

Table 3.2

Percentage agreement (bold) between randomly generated NZMG points within Gage's (1957) mapped lithological units and corresponding lithological units observed in the field.

Formations observed at randomly generated points		Formations predicted by map at randomly generated points							
		AL	**AF**	**Gr**	**Ot**	**Gl**	**Ku**	**Pk**	**Kk**
		n=13	*n=9*	*n=11*	*n=27*	*n=17*	*n=7*	*n=26*	*n=13*
Alluvium of the Low Terraces	**AL**	**69**						4	8
Alluvium of the Floodplains	**AF**		**60**			6	14		
Gravels of the High Terraces	**Gr**	8		**45**	7	6	29	12	15
Otekaike Limestone	**Ot**	8	20	45	**52**	18			
Glauconitic Sandstones & Greensands	**Gl**		20		41	**70**		31	
Kauru Formation	**Ku**						**57**	19	15
Papakaio Formation	**Pk**							**35**	8
Kakanui Metamorphic Group	**Kk**	15		10					**54**

There is a mean percentage agreement of 55% between predicted and observed lithological units, with the poorest agreement occurring on the mapped Papakaio Formation and the strongest agreement occurring on the mapped Glauconitic Sandstones and Greensands.

The discrepancies between predicted and observed lithological units are primarily an issue of scale and the ability of the original map data to accurately delineate the spatial occurrence of boundaries between units. In most instances where disagreements occur, the lithological units observed in the field correspond to mapped units that are directly adjacent to those predicted (Figure 3.3a). The one significant exception is the observed presence of Gravels of the High Terraces in locations where Kauru Formation was mapped, which probably reflected gravel colluvium derived from sources of higher elevation. In general, however, it appears that the closer sample points fell to mapped lithological unit boundaries, the greater the discrepancy between predicted and observed units. This highlights the inability of the map's original scale (1:63,360) to accurately resolve transitions between different lithological units, a drawback that is compounded by the error propagation discussed above.

It should be noted that apparent impurities in Gage's (1957) map units are paralleled by impurities in Wilson's (1970) SMUs. This is especially evident in comparing the purity of the Otekaike Limestone map unit (Table 3.2) with that of the Oamaru Series SMU (Table 3.1), which is formed in the Otekaike Limestone. Forty one percent of predicted Otekaike Limestone observations were in fact Glauconitic Sandstones and Greensands, and this error appears to be propagated into Wilson's (1970) map, with 33% of predicted Oamaru Series observations in fact being Tokarahi Series formed in the Glauconitic Sandstones and Greensands. Impurities within Gage's (1957) map unit may be caused by either inclusions of glauconitic sediments within the limestone, or map boundary errors that poorly delineate the contacts between the glauconitic sediments and overlying calcareous sediments. Whatever the source of error, the assumption that Wilson (1970) used Gage's (1957) geological data in the construction of his soil map suggests that any errors in delineation of lithological units may be propagated into the soil map.

3.2.2 Critical Analysis of Gage's (1957) Map for Quantitative Soil-Landscape Modelling

Despite evident limitations of map scale in the delineation of lithological unit boundaries, the limited detail and low reliability of Gage's (1957) original basemap, and the errors introduced an various stages of transformation from hard copy to digital maps, Gage's (1957) map was the most accurate and detailed representation of the spatial distribution of geological parent materials in the study area. In the absence of any other existing large-scale geological data, there was no other option for modelling geological parent materials.

The major drawback of Gage's (1957) map is that because of its scale, members within formations that are significant for the soil pattern not mapped. This is exemplified by Wilson's (1970) Airedale Series SMUs, which by definition occur on siltstones within the Gage's (1957) Kauru Formation. Gage (1957) could not delineate the siltstone members separate from the associated sandstone members within his map unit (on which Kauru Series SMUs occur) and hence the geological map has no predictive power in regard to separating Kauru Series (on Kauru Formation sandstones) from Airedale Series (on Kauru Formation siltstones). The result was that in the development of quantitative SLMs for the present work (Chapters 4 and 5) some soil series were unable to be separately modelled and were necessarily amalgamated into soil complexes. However, it was never necessary to create complexes of more than two soil series for this reason.

Figure 3.3b shows the edited form of Gage's (1957) map that was used in the development of quantitative SLMs for the study area (see Chapters 4 and 5). Lithological units that comprised very small percentages of the total area were not included in the analysis, and were amalgamated with adjacent lithological units (*e.g.* Kokoamu Greensand and Raki Siltstone were combined with Tapui Glauconitic Sandstone to form the Glauconitic Sandstones and Greensands lithological unit).

3.3 Digital Terrain Attribute Data

A description of the theoretical basis of digital terrain attributes was presented in Section 1.2.6. Presented below is a more detailed review of the digital terrain attributes (Figure 3.4) used in the development of quantitative SLMs for the study area shown in Chapters 4 and 5.

3.3.1 Elevation, Aspect, Slope, Profile Curvature and Plan Curvature

Elevation was represented by a 25 m resolution DEM provided by Landcare Research. The DEM was in integer form and was based on linear interpolation between known elevation points. These points had been digitised from topographic contour data and spot height data, and were supported by independent GPS-referenced point data. The integer form of the DEM meant that slopes occurred in small terraces as the DEM surface crossed each discrete 1 m elevation level. Also, due to the linear interpolation of the DEM, slope continuity was not modelled and the model had sharp inflections where smooth transitions may have actually occurred (J. Barringer, pers. comm.). To produce smoother slopes for more realistic results, the integer DEM was converted to a floating point grid using a 3×3 neighbourhood averaging algorithm in the Spatial Analyst extension of ArcView 3.1 GIS software (ESRI, 1996; see Figure 3.5a). This was the grid from which all further digital terrain attributes were derived.

Both aspect and slope were also derived using the ArcView 3.1 GIS software (ESRI, 1996). Aspect was derived with an algorithm that identified the down slope direction of the maximum rate of change in value from each grid cell to its neighbours, and compass bearings were ascribed to the output grid (Figure 3.5b). Slope was derived with an algorithm (Burrough, 1986) that identified the maximum rate of change in elevation value from each grid cell to its neighbours, and the output was in degrees (Figure 3.5c).

Profile curvature and plan curvature were derived with the Spatial Analyst extension of ArcView 3.1 GIS software (ESRI, 1996; Figures 3.5d and 3.5e), using algorithms that calculated the curvature of the surface at each grid cell centre. For profile curvature negative values indicated convexity and positive values indicated concavity, with values close to zero indicating planar slopes. For plan curvature positive values indicated convexity and negative values indicated concavity.

3.3.2 Log Upslope Area

Upslope area was calculated from the smoothed 25 m DEM using TARDEM software (Tarboton, 2000), with the output upslope area grid derived from an intermediate flow direction grid (Tarboton, 1997). The upslope (catchment) area was defined as contributing area per unit contour length, which was taken here as the grid cell size (Tarboton, 2000). Due to the very large grid cell value range produced, the upslope area grid is presented as the natural log transformation (Figure 2.5f)

3.3.3 Wetness Index and Stream Power Index

Both wetness index (WI, Figure 3.5g) and stream power index (SPI, Figure 3.5h) were calculated using the Map Calculator function in the Spatial Analyst extension of ArcView 3.1 GIS software (ESRI, 1996). WI was calculated using the equation

$$WI = \ln\left(\frac{A_s}{\tan\beta}\right)$$

Where A_s is the upslope area and β is slope. SPI was calculated using the equation

$$SPI = \ln\left(A_s \tan\beta\right)$$

Where A_s is the upslope area and β is slope.

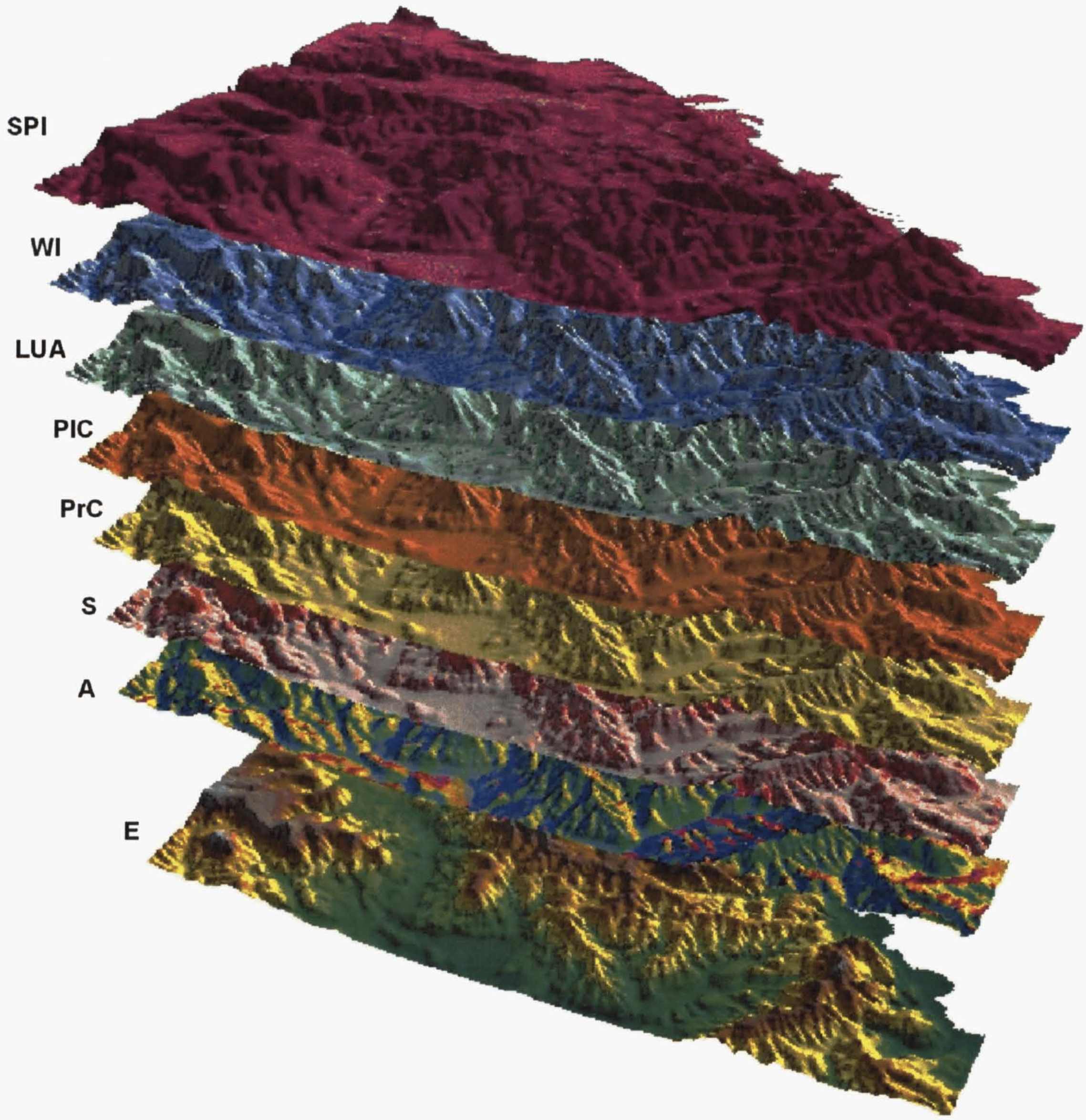


Figure 3.4

Digital terrain attributes used in the development of quantitative SLMs. E = Elevation; A = Aspect; S = Slope; PrC = Profile Curvature; PlC = Plan Curvature; LUA = Log Upslope Area; WI = Wetness Index; SPI = Stream Power Index.

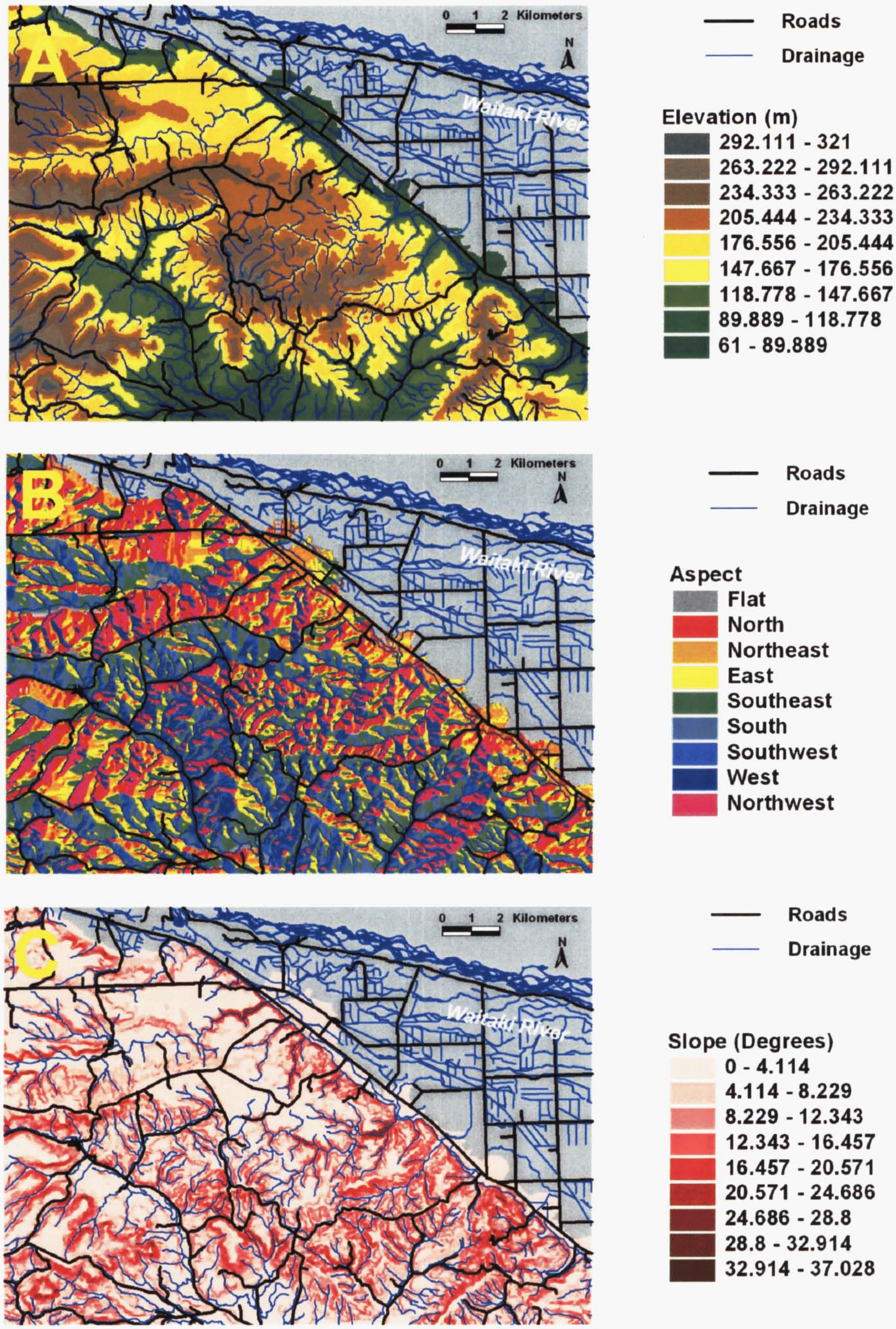


Figure 3.5

Digital terrain attributes of the study area.

A) 25 m resolution DEM, from which all other digital terrain attributes were derived.

B) Aspect in degrees.

C) Slope in degrees.

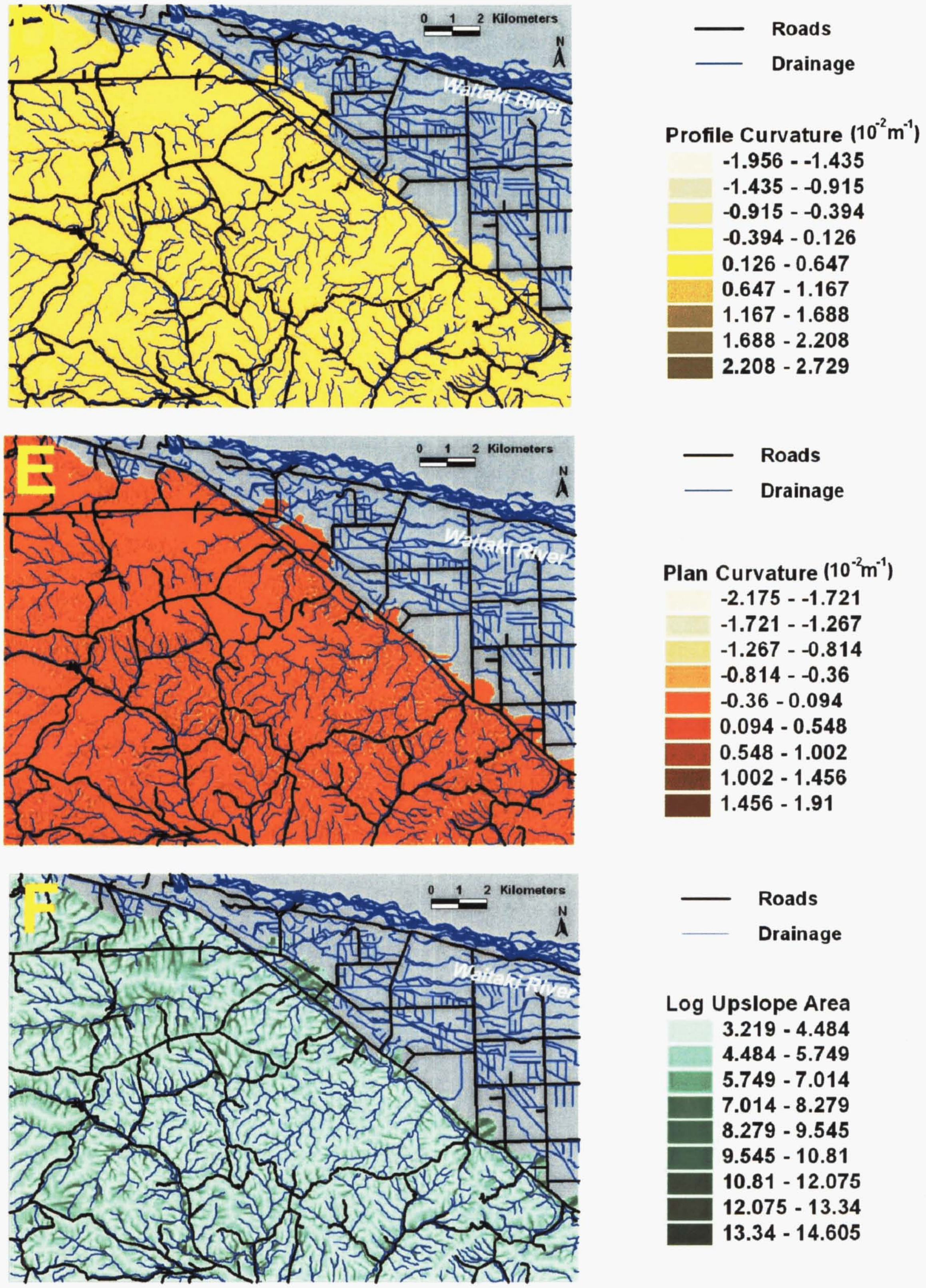


Figure 3.5 continued

Digital terrain attributes of the study area.

D) Profile Curvature.

E) Plan Curvature.

F) Log Upslope Area.

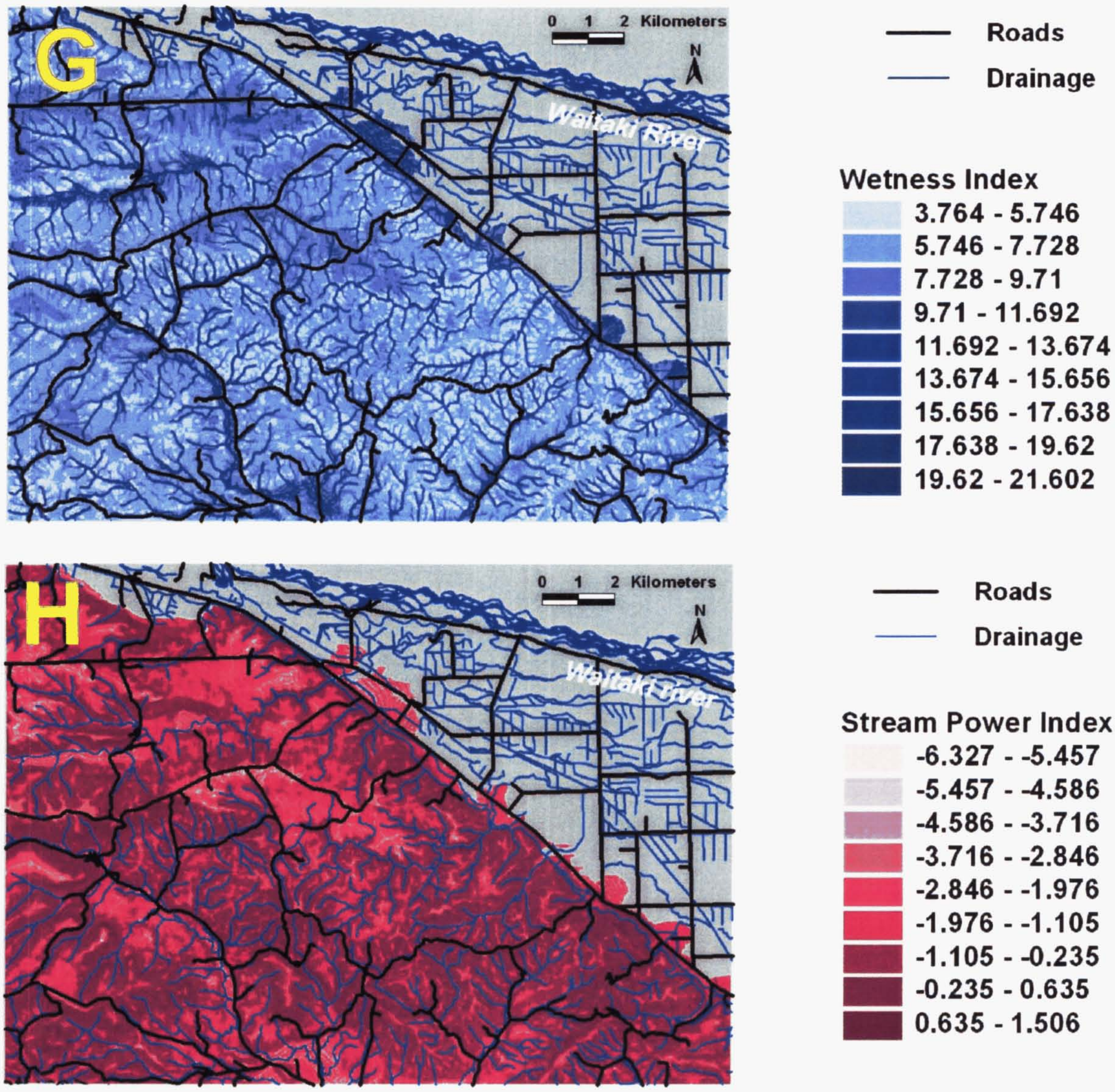


Figure 3.5 continued

Digital terrain attributes of the study area.

G) Wetness Index.

H) Stream Power Index.

Chapter 4

A Quantitative Soil-Landscape Model of the Study Area Based on Pre-Existing Map Data

4.1 Introduction

A quantitative SLM of the study area was developed using the pre-existing soil data of Wilson (1970), the pre-existing lithological data of Gage (1957) and digital terrain attribute data layers (see Chapter 3). Since this SLM was one of two developed for the present work, it will be referred to as quantitative SLM 1 (qSLM 1). This model was an attempt to quantitatively define Wilson's (1970) conceptual SLMs of the study area. In doing so, statistical functions were derived that best discriminated between Wilson's (1970) soil series-based SMUs on the basis of digital terrain attributes. Analysis was done separately for each lithological unit. This is because lithology is a very important predictor for soil series, yet it could not be introduced as a variable into the DFA because it is categorical in nature, not numeric. As discussed in Section 3.1.2, the analysis is an attempt to predict SMUs along with their inherent impurities.

4.2 Development of qSLM 1

The major steps involved in the development of qSLM 1 are shown in Figure 4.1.

4.2.1 Sampling & Data Generation

To determine the spatial extent of Wilson's (1970) SMUs on their respective lithological units, Wilson's (1970) soil map (Figure 3.2b) was intersected with Gage's (1957) geological map (Figure 3.3b) using ArcView GIS software (ESRI, 1996). The resulting data layer showed Wilson's (1970) SMUs distributed across individual lithological units (Figure 4.2). Boundary errors occurred due to differences in map scales, meaning that some SMUs were included on lithological units that by definition they could not occur upon. These boundary error polygons were ignored for the purposes of the analysis and were deleted from the data layer. The following analysis did not include the alluvium of the floodplains and alluvium of the low terraces because digital terrain attributes have no discriminatory power on these flat units, and the relevant soils (Awamoko/Enfield and Georgetown) were simply ascribed to these lithological units.

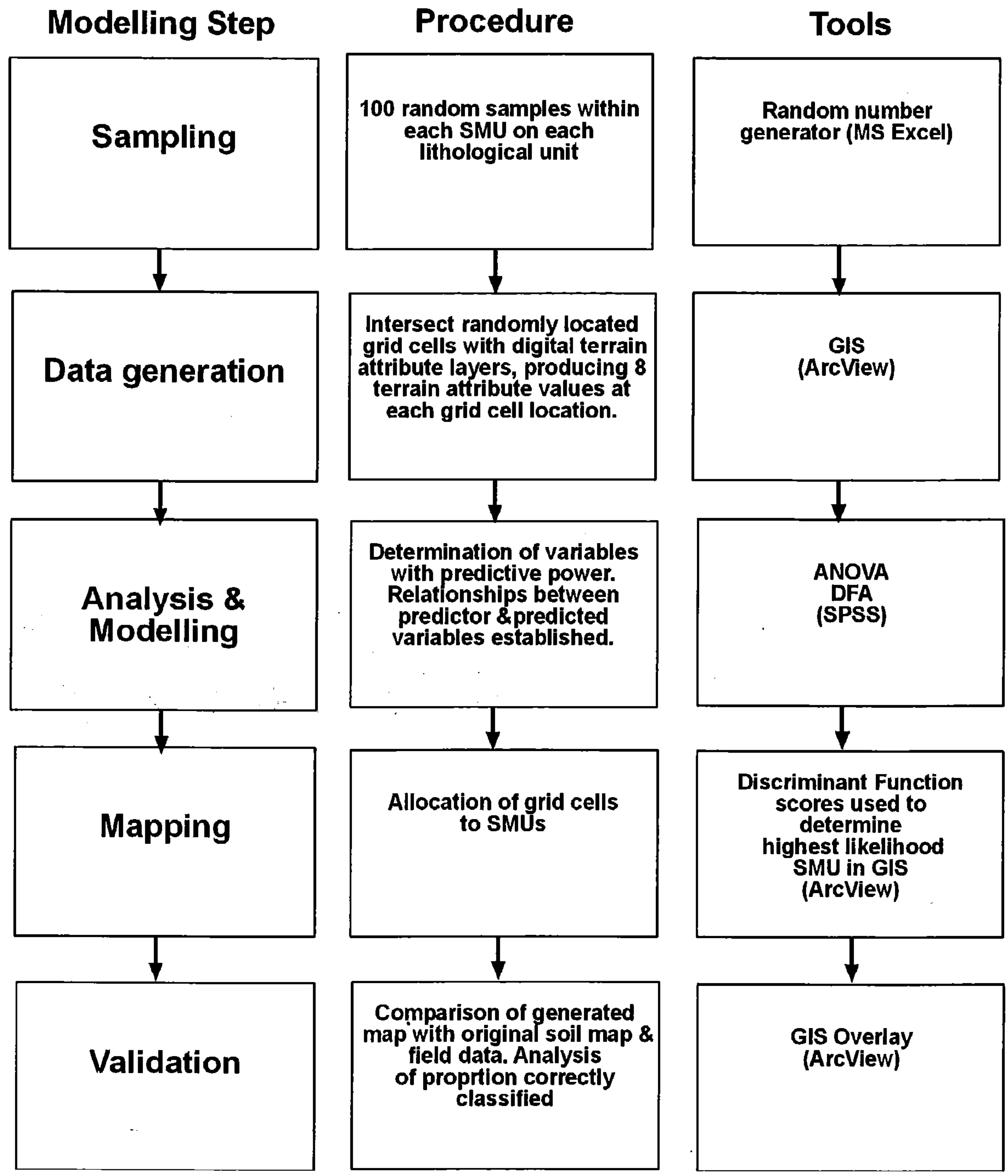


Figure 4.1

The major steps that were undertaken in the development of qSLM 1.

For a given lithological unit, randomly located points were intersected with the SMUs occurring on that lithological unit. One hundred randomly located points were selected for each SMU, coded according to the SMU they fell within, then converted to a 25 m grid raster cover for intersection with the digital terrain attribute grids (Figure 4.2). After the intersection procedure each grid cell, coded for the SMU to which it belonged, had eight terrain attributes associated with it. These eight predictor variables were used in the subsequent analysis phase (Figure 4.1)

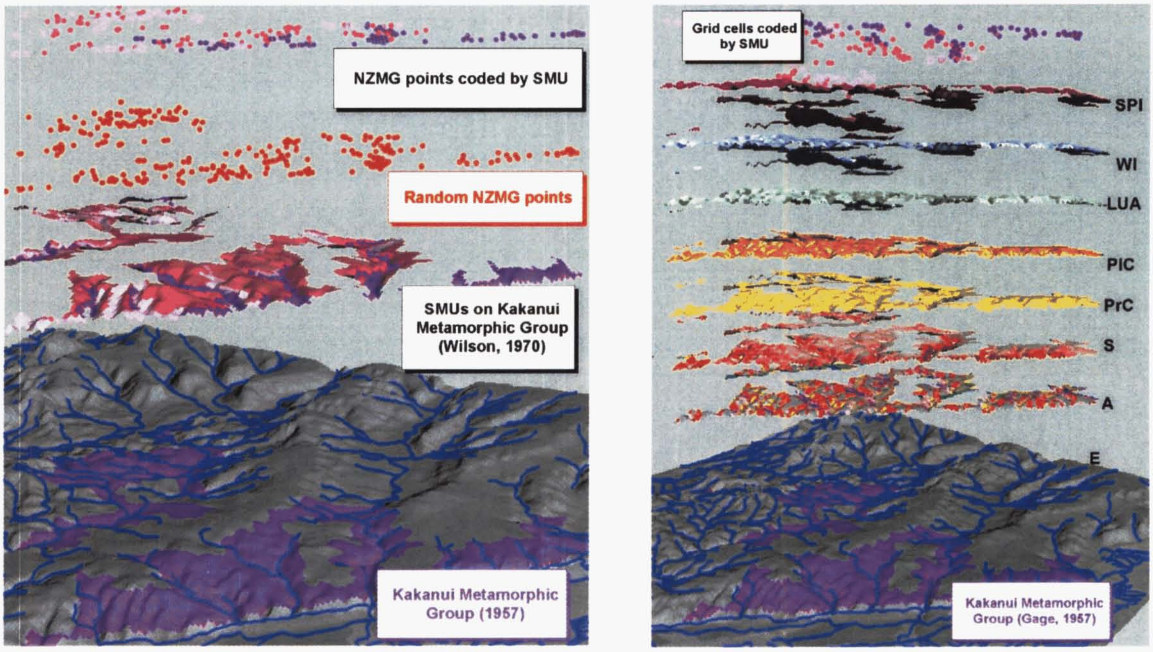


Figure 4.2

Example of the initial stages of the development of qSLM 1 using Wilson's (1970) SMUs on the Kakanui Metamorphic Groups (Gage, 1957) and digital terrain attributes.

Left: Sampling and data gathering to determine the soil map delineations that occur on the lithological unit. Randomly generated points were then intersected with the delineations to generate 100 randomly located points for each SMU.

Right: The randomly generated points coded by SMU were converted to 25 m grid cells and intersected with all the digital terrain attributes within the spatial extent of the Kakanui Metamorphic Group. The result is each SMU-coded grid cell being attached to the digital terrain attributes at that specific grid cell location, and the capture of data amenable to statistical analysis. E = Elevation; A = Aspect; S = Slope; PrC = Profile Curvature; PlC = Plan Curvature; LUA = Log Upslope Area; WI = Wetness Index; SPI = Stream Power Index.

4.2.2 Analysis & Modelling

Statistical analysis was carried out using SPSS 10.0.1 software (SPSS Inc., 1999). Analysis of variance was performed for each lithological unit to see if there were statistically significant differences in mean digital terrain attribute values between SMUs. DFA was used to generate functions discriminating between SMUs on the basis of digital terrain attribute values.

Two discriminant analyses using digital terrain attributes were conducted for each SMU on each lithological unit. In the interests of parsimony, the first discriminant analysis used only those digital terrain attributes that showed significant differences ($P < 0.05$) in mean values between SMUs from the univariate testing. This was a stepwise estimation where the independent digital terrain attribute variables were entered into the DFA one at a time on the basis of their discriminating power. Terrain attribute variables that did not enter the model were either not useful in discriminating between SMUs, or were correlated with variables used earlier in the stepwise analysis and therefore deemed superfluous. Elevation was excluded from the analysis despite showing significant differences between SMUs on some lithological units because this terrain attribute was not considered to be a useful predictor variable outside of the study area. The second analysis was a simultaneous estimation where all independent variables were considered concurrently, so that the discriminant function was computed based on the entire set of variables regardless of the discriminating power of each variable. Therefore all terrain attributes were used, regardless of P value and including elevation, to assess the relative improvement of SMU discrimination over using only digital terrain attribute variables where $P < 0.05$.

Classification functions and classification results for each SMU on each lithological unit were derived from the stepwise analysis. The classification functions were used to allocate observations (SMU-coded grid cells) by inserting the observation's values for the independent digital terrain attribute variables in the classification function, and a classification score for each SMU group was calculated for that observation. The observations were then allocated to the group with the highest classification score.

For all lithological units both slope and stream power index consistently showed significant differences between SMUs (Table 4.1), and where these values were in agreement with Wilson's (1970) conceptual SLMs and reflected relationships observed in the field for this study, physical interpretations of these digital terrain attributes were possible. Mean slope values for Ngapara/Timaru Soils were lower than those for Brookstead/Ardgowan Soils for all lithological units, confirming Wilson's (1970) conceptual models of these soils' slope characteristics (see Section 2.7), and also supported by field observations for the present work. For the lithological units Glauconitic Sandstones and Greensands, Kauru Formation and the Kakanui Metamorphic Group, soils on geological parent materials showed steeper slopes than the soils on loessial parent materials, further confirming Wilson's (1970) SLMs. Physical interpretations suggest that slope is an important factor influencing loess accumulation, with significant accumulations of loess occurring on shallower slopes and absent on the steepest slopes where the erosive power of overland flow is greatest (as reflected by stream power index). On the Otekaike Limestone lithological unit Waikakahi Soils showed mean slope angles intermediate between Ngapara/Timaru and Brookstead/Ardgowan Soils. These soil-landscape relationships are in disagreement with Wilson's (1970) conceptual SLMs. Roseberry Soils showed steeper mean slope angles than those for Oamaru Soils, which confirmed aspects of Wilson's (1970) models and are supported by field observations. Again, physical interpretations suggest the importance of slope and stream power index in controlling loess accumulation. On Gravels of the High Terraces Taiko Soils showed lower mean slope values than Ngapara/Timaru Soils, and on the Papakaio Formation Papakaio/Kauru Soils showed lower mean slope values than Brookstead/Ardgowan Soils. Neither of these results agreed with Wilson's (1970) original conceptual models nor are intuitively reasonable. This is most likely a result of the inability of the DEM resolution to capture microtopographic variation that is redistributing loess to expose gravel on flatter surfaces.

The discrepancies between SMU terrain attributes and Wilson's (1970) conceptual models, as well as field observations in the course of the present work, are attributable to three main sources of error. First, there may be inconsistencies in Wilson's (1970) map where SMUs have been incorrectly ascribed to particular SLUs. Second, DEM errors may result in counterintuitive terrain attributes being associated with SMUs. Third, errors in the registration of the original soil map data may have resulted in incorrect associations between SLUs/SMUs and underlying digital terrain attributes.

Table 4.1

Mean and standard deviation of digital terrain attributes within each soil series/soil complex (after Wilson, 1970) on each lithological unit (after Gage, 1957) used in the qSLM 1 analysis.

		E	A	S	PrC	PlC	LUA	WI	SPI
		Mean/ Standard Deviation							
Gravels of the High Terraces	**Ng/Ti** n=100	218/ 23	163/ 118	2.8/ 2.3	-0.03/ 0.09	0.005/ 0.1	4.8/ 1.3	8.2/ 1.5	-1.9/ 1.1
	Br/Ar n=100	226/ 26	145/ 107	6.5/ 4.6	-0.02/ 0.2	-0.04/ 0.2	5.3/ 1.6	7.8/ 2.2	-0.9/ 0.9
	Tk n=100	199/ 31	112/ 118	2.7/ 3.5	-0.05/ 0.1	0.005/ 0.1	5.1/ 1.1	8.7/ 1.5	-1.6/ 1.6
	F	**25.7*****	**5.2****	**36.0*****	**0.9**	**2.9**	**3.9***	**6.2****	**33.0*****
Otekaike Limestone	**Ng/Ti** n=100	244/ 37	131/ 111	4.9/ 3.8	-0.05/ 0.2	0.02/ 0.1	4.6/ 0.9	7.4/ 1.1	-1.3/ 1.0
	Br/Ar n=100	238/ 17	183/ 106	9.2/ 4.3	0.007/ 0.2	-0.02/ 0.2	5.2/ 1.4	7.2/ 1.7	-0.4/ 0.6
	Wk n=100	211/ 32	151/ 127	6.9/ 4.3	-0.06/ 0.2	0.007/ 0.2	5.0/ 1.6	7.3/ 1.8	-0.8/ 0.8
	Om n=100	213/ 30	155/ 127	12.5/ 6.0	0.03/ 0.4	0.02/ 0.3	5.0/ 1.4	6.6/ 1.6	-0.07/ 0.6
	Rb n=100	218/ 15	203/ 93	13.4/ 4.3	-0.06/ 0.4	0.01/ 0.2	4.9/ 0.7	6.4/ 0.7	0.09/ 0.4
	F	**29.2*****	**6.1*****	**61.7*****	**2.0**	**0.7**	**3.6****	**9.3*****	**64.0*****

Digital Terrain Attributes

E = Elevation (m)
A = Aspect (bearing in degrees)
S = Slope in degrees
PrC = Profile Curvature
$^+$ve – concave
$^-$ve – convex
PlC = Plan Curvature
$^+$ve – convex
$^-$ve – concave
LUA = Log Upslope Area
WI = Wetness Index
SPI = Stream Power Index

Soil Series & Complexes

Ng/Ti = Ngapara/Timaru
Br/Ar = Brookstead/Ardgowan
Tk = Taiko
Wk = Waikakahi
Om = Oamaru
Rb = Roseberry

*** = P < 0.05**
**** = P < 0.01**
***** = P < 0.00**

Continued overleaf

Table 4.1 continued

		Mean/ Standard Deviation							
		E	**A**	**S**	**PrC**	**PlC**	**LUA**	**WI**	**SPI**
Glauconitic Sandstones & Greensands	**Ng/Ti** *n*=100	175/ 46	174/ 107	5.6/ 3.9	0.03/ 0.1	-0.002/ 0.1	5.0/ 1.4	7.5/ 1.5	-1.0/ 0.8
	Br/Ar *n*=100	209/ 27	161/ 91	10.1/ 4.8	0.06/ 0.2	-0.0004/ 0.2	5.2/ 1.4	7.1/ 1.7	-0.2/ 0.5
	To *n*=100	183/ 31	184/ 89	11.2/ 4.8	0.01/ 0.2	0.02/ 0.2	5.1/ 1.2	6.9/ 1.5	-0.2/ 0.6
	F	**25.4*** **	**1.5**	**43.1*** **	**1.6**	**0.6**	**1.0**	**4.4***	**50.0*** **
Kauru Formation	**Ng/Ti** *n*=100	154/ 42	193/ 96	6.3/ 3.7	-0.006/ 0.2	-0.006/ 0.2	4.8/ 1.3	7.2/ 1.6	-0.9/ 0.7
	Br/Ar *n*=100	164/ 44	163/ 72	8.5/ 4.6	0.07/ 0.2	-0.003/ 0.3	5.0/ 1.5	7.2/ 2.0	-0.6/ 0.7
	Ai/Ku *n*=100	152/ 35	175/ 103	9.2/ 5.6	-0.009/ 0.2	0.005/ 0.2	5.0/ 1.5	7.0/ 1.9	-0.5/ 0.8
	F	**2.3**	**2.8**	**10.2*** **	**5.4** **	**0.1**	**1.0**	**0.3**	**8.8*** **

Digital Terrain Attributes

E = Elevation (m)
A = Aspect (bearing in degrees)
S = Slope in degrees
PrC = Profile Curvature
$^{+}$ve – concave
$^{-}$ve – convex
PlC = Plan Curvature
$^{+}$ve – convex
$^{-}$ve – concave
LUA = Log Upslope Area
WI = Wetness Index
SPI = Stream Power Index

Soil Series & Complexes

Ng/Ti = Ngapara/Timaru
Br/Ar = Brookstead/Ardgowan
To = Tokarahi
Ai/Ku = Airedale/Kauru

* = P < 0.05
** = P < 0.01
*** = P < 0.001

Continued overleaf

Table 4.1 continued

		Mean/ Standard Deviation							
		E	A	S	PrC	PlC	LUA	WI	SPI
Papakaio Formation	**Ng/Ti** *n*=100	171/ 50	176/ 104	6.1/ 4.2	-0.06/ 0.2	-0.00006/ 0.2	4.9/ 1.5	7.4/ 1.9	-1.0/ 0.9
	Br/Ar *n*=100	184/ 39	165/ 95	10.7/ 9.9	0.1/ 0.3	-0.03/ 0.3	5.1/ 1.5	7.0/ 2.0	-0.2/ 0.6
	Pk/Ku *n*=100	183/ 47	172/ 107	9.9/ 5.0	0.01/ 0.32	-0.03/ 0.3	5.0/ 1.5	6.9/ 1.9	-0.4/ 0.7
	F	**2.4**	**0.3**	**27.0*** **	**12.5*** **	**0.5**	**0.9**	**2.0**	**30.9*** **
Kakanui Metamorphic Group	**Ng/Ti** *n*=100	193/ 26	180/ 104	6.1/ 3.9	-0.07/ 0.2	0.02/ 0.2	4.9/ 1.3	7.4/ 1.6	-1.0/ 0.9
	Br/Ar *n*=100	188/ 32	175/ 115	8.6/ 5.6	0.05/ 0.3	-0.03/ 0.3	5.2/ 1.8	7.4/ 2.2	-0.6/ 0.8
	Bo *n*=100	157/ 21	163/ 126	11.2/ 6.3	0.1/	-0.009/ 0.3	5.5/ 2.4	7.4/ 3.1	-0.3/ 0.8
	F	**54.3*** **	**0.6**	**22.4*** **	**9.0*** **	**0.6**	**2.6**	**0.0**	**18.4*** **

Digital Terrain Attributes

E = Elevation (m)
A = Aspect (bearing in degrees)
S = Slope in degrees
PrC = Profile Curvature
  +ve – concave
  -ve – convex
PlC = Plan Curvature
  +ve – convex
  -ve – concave
LUA = Log Upslope Area
WI = Wetness Index
SPI = Stream Power Index

Soil Series & Complexes

Ng/Ti = Ngapara/Timaru
Br/Ar = Brookstead/Ardgowan
Pk/Ku = Papakaio/Kauru
Bo = Bortons

* = P < 0.05
** = P < 0.01
*** = P < 0.001

Other SMUs showed significant differences between mean digital terrain attribute values depending on the lithological unit on which they occur (Table 4.1). Elevation was a significant ($P < 0.001$) variable distinguishing SMUs on all lithological units except for the Kauru and Papakaio Formations, although this terrain attribute was not used in subsequent analysis because it was not considered a useful predictor variable outside of the study area. Both profile curvature and wetness index showed significant differences in mean values between SMUs on half of the lithological units. Aspect and LUA were significant only on

Gravels of the High Terraces and Otekaike Limestone. No physical explanation for the significance of aspect is obvious. The regional dip and strike of lithological units was considered for its influence on erosion processes but mean aspects for different SMUs showed no explicable patterns. There was no significant difference in plan curvature values between SMUs on any lithological unit.

The DFA ascribed discriminant scores to all of the training set grid cells within SMU groups, which were then averaged to derive group centroids. The group centroids indicated the most typical location in N-dimensional space of any individual from a particular group, and distances between group centroids were a measure of the degree of discrimination along the terrain attribute dimension being tested. The group centroids for each SMU on each lithological unit are plotted on axes of discrimination in Figure 4.3. Axes on the left show those group centroids calculated from discriminant functions based on stepwise analysis using digital terrain attributes where $P < 0.05$, with the terrain attribute variables used in the final discrimination noted. Axes on the right show group centroids for the same SMUs calculated from discriminant functions based on simultaneous analysis using all digital terrain attributes. The farther apart the SMU group centroids, the better they are discriminated from each other.

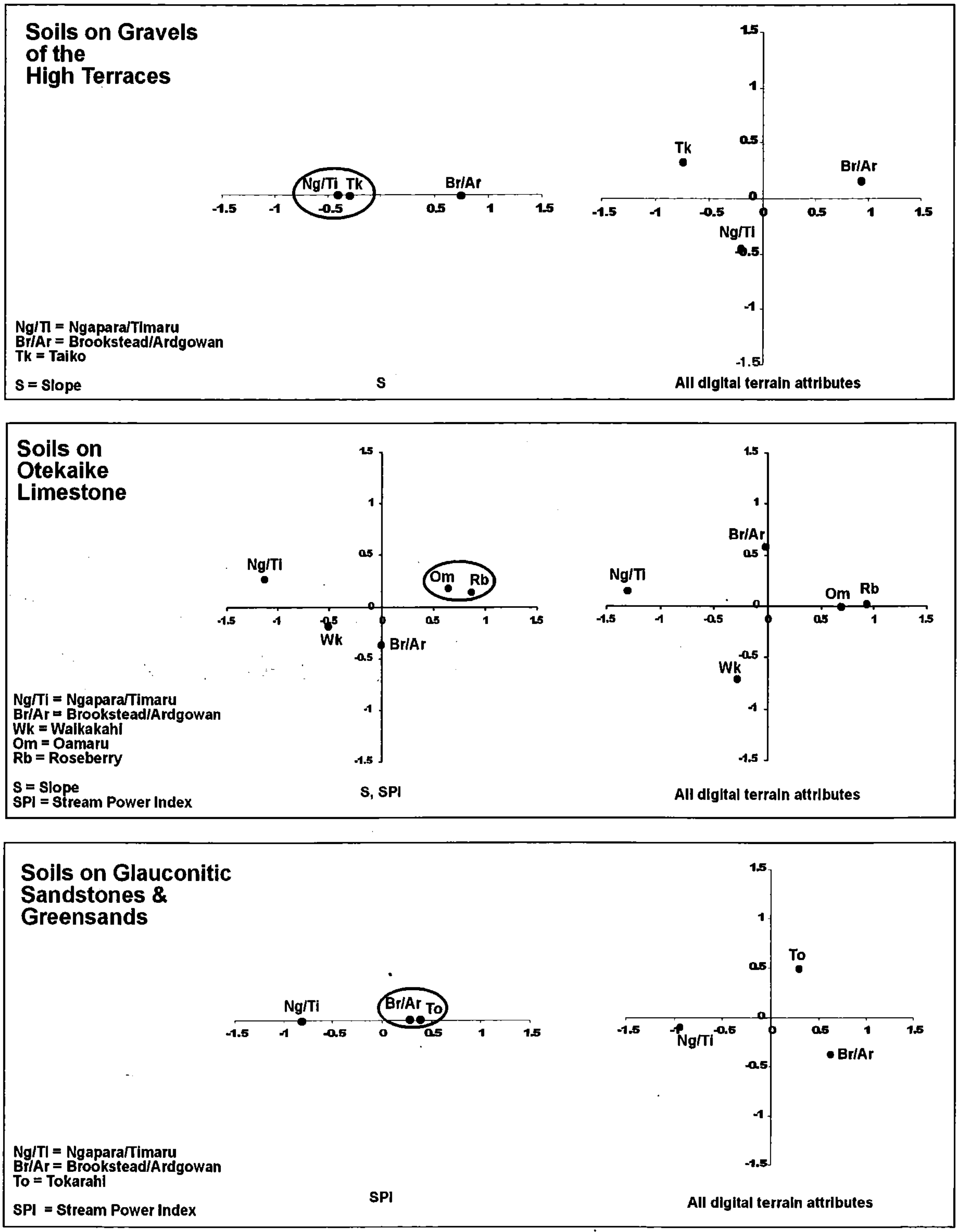


Figure 4.3

Group centroids for SMUs calculated from DFA and plotted on discriminant axes. Axes on the left show those centroid functions used for the development of qSLM 1, derived from stepwise analysis using significant univariate predictors. Centroids in ellipses are not significantly discriminated from each other. Axes on the right show centroid functions derived from simultaneous DFA using all digital terrain attributes.

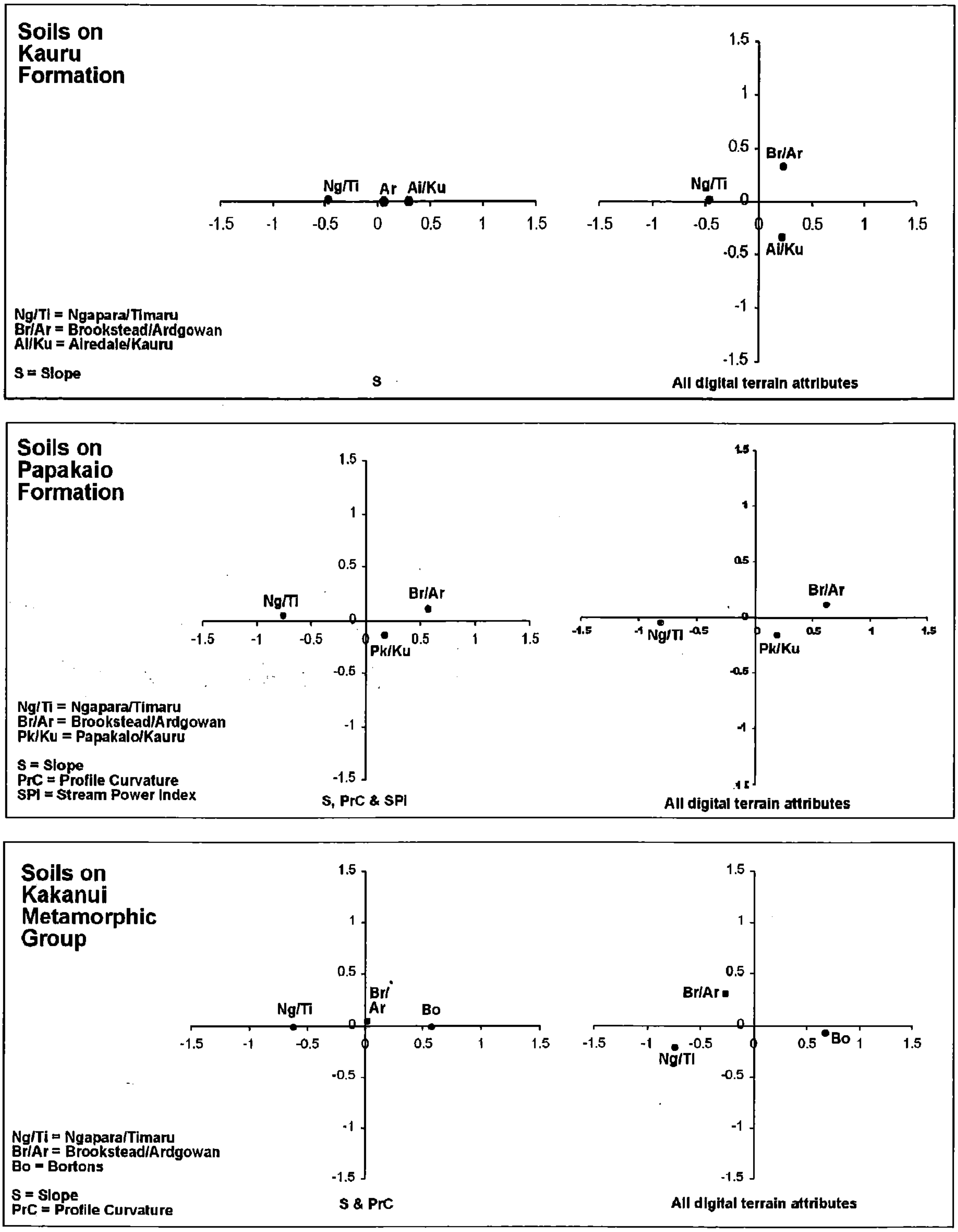


Figure 4.3 continued

For the lithological units Gravels of the High Terraces, Glauconitic Sandstones and Greensands and Kauru Formation, stepwise analysis produced discriminant functions that separated SMU centroids based on only one digital terrain attribute, with centroids plotted on a single discriminant axis (Figure 4.3, axes on left). SMUs on Gravels of the High Terraces were discriminated on the basis of slope, with both Ngapara/Timaru and Taiko

Soils both well discriminated from Brookstead/Ardgowan Soils but showing no discrimination from each other. Similarly, SMUs on Glauconitic Sandstones and Greensands were discriminated on the basis of stream power index, with both Brookstead/Ardgowan and Tokarahi Soils well discriminated from Ngapara/Timaru Soils but showing no discrimination from each other. For SMUs on Kauru Formation, the Ngapara/Timaru, Brookstead/Ardgowan and Airedale/Kauru Soils group centroids are clearly discriminated on the basis of slope, although the relatively small separation distance between centroids on the discriminant axis implies only moderately successful discrimination.

Stepwise analysis for the other three lithological units required more than one digital terrain attribute variable to discriminate between SMU groups and maximise separation distance between group centroids. For SMUs on Otekaike Limestone, slope and stream power index were ultimately used in the final discriminant analysis. Centroids for Ngapara/Timaru, Waikakahi and Brookstead/Ardgowan Soils were well separated from each other and the Oamaru/Roseberry pair, but Oamaru and Roseberry were not discriminated from each other. SMUs on Papakaio Formation required three digital terrain attributes from the stepwise analysis (slope, profile curvature and stream power index) to maximise group separation, and centroids are well separated with each occurring in different quadrants of the graph, implying good discrimination. SMUs on the Kakanui Metamorphic Group similarly show good discrimination with separation of group centroids based on slope and stream power index, although discrimination appears greatest along only one of the two discriminant axes used.

Two things are clear from the axes on the right of Figure 4.3: 1) the use of all digital terrain attributes in simultaneous DFA improved the separation distance between group centroids for those lithological units where only one discriminant variable was generated in the stepwise analysis (*i.e.* SMUs on Gravels of the High Terraces, Glauconitic Sandstones and Greensands and Kauru Formation) and 2) the use of all digital terrain attributes did not markedly improve separation distances between group centroids for those lithological units that had already produced two discriminant variables from the stepwise analysis (*i.e.* SMUs on Otekaike Formation, Papakaio Formation and the Kakanui Metamorphic Group). These cases suggest that the use of the most apparently parsimonious combination of digital terrain variables did not necessarily lead to the most successful discrimination, and that where satisfactory discrimination was achieved with stepwise analysis the use of extra digital terrain attribute variables was superfluous.

In addition, the poor separation distances between pairs of SMU centroids (Figure 4.3, in ellipses) means that there is essentially no discrimination between Ngapara/Taiko SMUs on Gravels of the High Terraces, Oamaru Roseberry SMUs on Otekaike Limestone and Tokarahi/Brookstead SMUs on Glauconitic Sandstones and Greensands. This is illustrated in Figure 4.4, where the SMU discriminant functions are graphed for each SMU on Gravels of the High Terraces. There is no effective discrimination between Ngapara/Timaru and Taiko Soils, therefore these units were combined to form a single complex for purposes of mapping. The same was done for Oamaru/Roseberry and Tokarahi/Brookstead Soils on the Otekaike Limestone and Glauconitic Sandstones and Greensands, respectively.

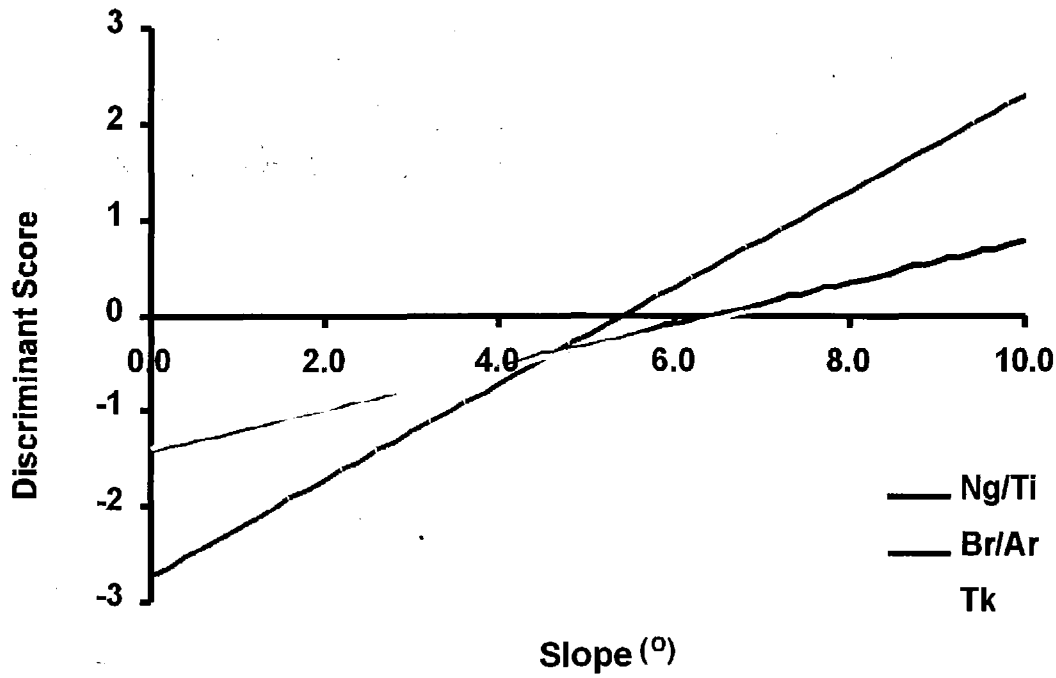


Figure 4.4

Discriminant function scores based on slope for SMUs on Gravels of the High Terraces. Note that that there is essentially no discrimination between Ngapara/Timaru (Ng/Ti) and Taiko (Tk) soils.

Classification functions and success of classification results derived from the stepwise DFA are shown in Table 4.2. Also shown for comparison are classification results derived from the simultaneous analysis. It was evident that the mean scores (% correctly classified) derived from stepwise analysis for SMUs on all lithological units were in general poor (39 – 56%). Individual SMU classification scores *within* lithological units, however, showed a wider range of classification results. The widest range was that of SMUs on Otekaike

Limestone with only 9% of Oamaru Soils correctly classified, and 67% of Roseberry Soils correctly classified. For each of the other five lithological units, two of the three SMUs approached or exceeded 50% correct classification at the expense of the third SMU, which generally showed a much lower classification score.

The results of the simultaneous DFA all showed higher mean percentages of correctly classified cases than for those derived from the stepwise analyses (Table 4.2). For SMUs on Gravels of the High Terraces, Glauconitic Sandstones and Greensands and Kauru Formation mean classification scores improved by 14%, 8% and 8% respectively, an improvement that paralleled the improved separation distances between group centroids plotted in Figure 4.3. For SMUs on Otekaike Limestone, Papakaio Formation and the Kakanui Metamorphic Group mean classification scores improved by 5%, 2% and 9%, respectively. This result again reflected improved discrimination.

Table 4.2

Classification functions and classification results from stepwise and simultaneous DFA.

		Classification Functions	Stepwise Analysis % of original grouped cases correctly classified		Simultaneous Analysis % of original grouped cases correctly classified	
Gravels of the High Terraces	**Ng/Ti**	(S x 0.219) – 1.407		20		58
	Br/Ar	(S x 0.208) – 1.376		73		70
	Tk	(S x 0.504) – 2.726		60		67
			Mean	**51**	**Mean**	**65**
Otekaike Limestone	**Ng/Ti**	(S x 1.644) – (SPI x 11.290) – 13.012		51		52
	Br/Ar	(S x 1.543) – (SPI x 8.853) – 10.269		39		54
	Wk	(S x 1.544) – (SPI x 9.734) – 10.782		28		39
	Om	(S x 1.797) – (SPI x 9.653) – 13.206		9		24
	Rb	(S x 1.803) – (SPI x 9.368) – 13.283		67		50
			Mean	**39**	**Mean**	**44**
Glauconitic Sandstone & Greensands	**Ng/Ti**	(SPI x -2.379) – 2.248		69		69
	Br/Ar	(SPI x -0.529) – 1.156		37		60
	To	(SPI x -0.391) – 1.130		62		56
			Mean	**56**	**Mean**	**62**

Soil Series & Soil Complexes

Ng/Ti = Ngapara/Timaru
Br/Ar = Brookstead/Ardgowan
Wk = Waikakahi
Om = Oamaru
Rb = Roseberry
To = Tokarahi

Digital Terrain Attributes (P < 0.001)

S = Slope in degrees
SPI = Stream Power Index

Continued overleaf

Table 4.2 continued

		Classification Functions	Stepwise Analysis		Simultaneous Analysis	
			% of original grouped cases correctly classified		% of original grouped cases correctly classified	
Kauru Formation	**Ng/Ti**	(S × 0.303) – 2.054		58		51
	Br/Ar	(S × 0.393) – 2.703		18		53
	Ai/Ku	(S × 0.442) – 3.124		48		44
			Mean	**41**	**Mean**	**49**
Papakaio Formation	**Ng/Ti**	(S × 1.730) + (PrC × 4.210) – (SPI × 10.722) – 11.687		65		68
	Br/Ar	(S × 1.892) + (PrC × 7.588) – (SPI × 10.180) – 12.806		54		55
	Pk/Ku	(S × 1.832) + (PrC × 5.756) – (SPI × 10.105) – 12.043		30		32
			Mean	**50**	**Mean**	**52**
Kakanui Metamorphic Group	**Ng/Ti**	(S × 0.206) – (PrC × 0.194) – 1.730		72		62
	Br/Ar	(S × 0.305) – (PrC × 1.152) – 2.449		17		33
	Bo	(S × 0.398) – (PrC × 2.052) – 3.453		55		76
			Mean	**48**	**Mean**	**57**

Soil Series & Soil Complexes

Ng/Ti = Ngapara/Timaru
Br/Ar = Brookstead/Ardgowan
Ai/Ku = Airedale/Kauru
Pk/Ku = Papakaio/Kauru
Bo = Bortons

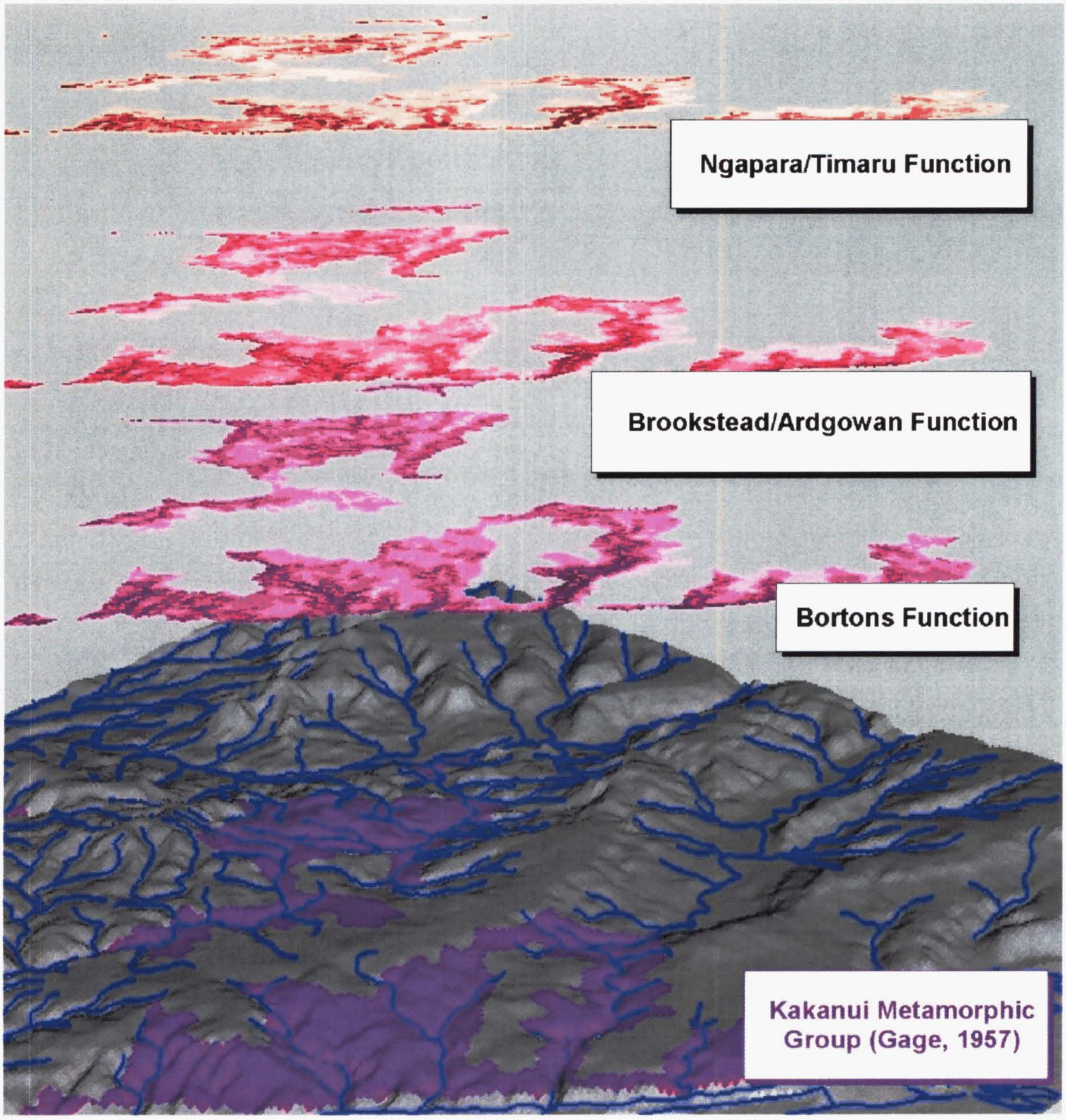
Digital Terrain Attributes (P < 0.001)

S = Slope in degrees
PrC = Profile Curvature
SPI = Stream Power Index

4.2.3 Mapping

The stepwise discriminant functions described earlier, which form qSLM 1, were used to derive a soil map. These stepwise functions were selected over the simultaneous functions because of they used a more parsimonious combination of variables. Consider the set of discriminant functions that apply to the SMUs of a given lithological unit (Table 4.2), and a grid cell within that unit. The scores calculated from the discriminant functions at the grid cell are directly proportional to the probability that the cell belongs to the SMU associated with each discriminant function. Hence, the mapping procedure involved determining the highest discriminant scores for all grid cells and then allocating grid cells to the SMU whose discriminant function produced the highest score.

This process is illustrated for SMUs on the Kakanui Metamorphic Group in Figures 4.5-4.7. Figure 4.5 shows the discriminant function value ranges for the predicted SMUs, and Figure 4.6 shows those grid cells coded by SMU with the highest discriminant scores. The amalgamation of these coded cells is shown in Figure 4.7, which illustrates the spatial distribution of the most probable SMUs for Kakanui Metamorphic Group. For the lithological units Gravels of the High Terraces, Otekaike Limestone and Glauconitic Sandstones and Greensands, SMUs that were unable to be discriminated from each other in the DFA (see Section 4.2.2 and Figure 4.3 above) were amalgamated into soil complexes. This process was conducted for all SMUs on all lithological units, and the results were combined to produce a final soil map derived from qSLM 1 (Figure 4.8).



Ngapara/Timaru Function	Brookstead/Ardgowan Function	Bortons Function
-2.017 - -1.243	-4.314 - -2.962	-6.959 - -5.014
-1.243 - -0.468	-2.962 - -1.611	-5.014 - -3.069
-0.468 - 0.306	-1.611 - -0.26	-3.069 - -1.124
0.306 - 1.08	-0.26 - 1.092	-1.124 - 0.82
1.08 - 1.854	1.092 - 2.443	0.82 - 2.765
1.854 - 2.628	2.443 - 3.794	2.765 - 4.71
2.628 - 3.402	3.794 - 5.146	4.71 - 6.655
3.402 - 4.177	5.146 - 6.497	6.655 - 8.6
4.177 - 4.951	6.497 - 7.848	8.6 - 10.545

Figure 4.5

Example of classification function value ranges for each of the predicted SMUs on the Kakanui Metamorphic Group (Gage, 1957).

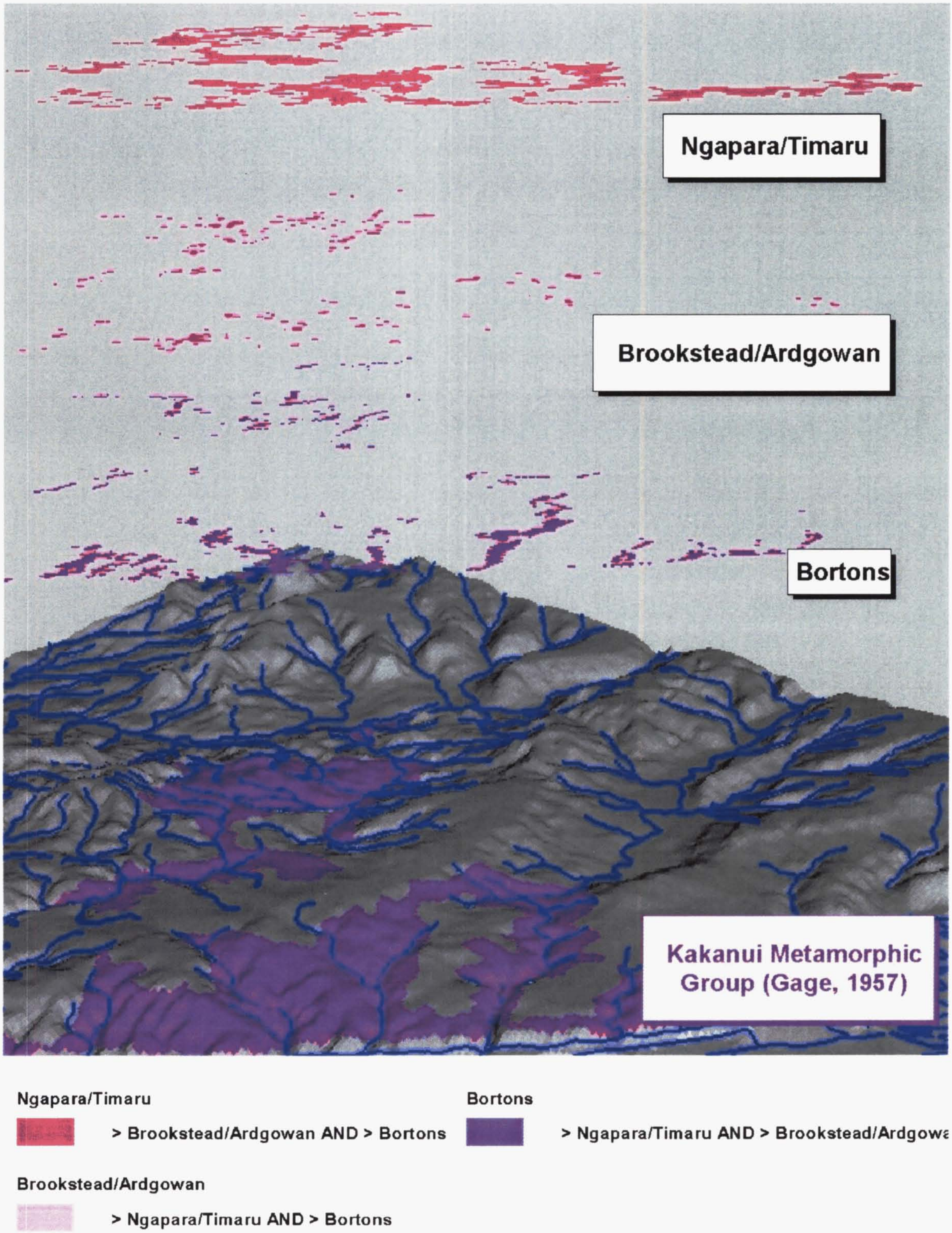


Figure 4.6

Example of predicted SMUs based upon the highest classification function score at each individual grid cell location on the Kakanui Metamorphic Group (Gage, 1957).

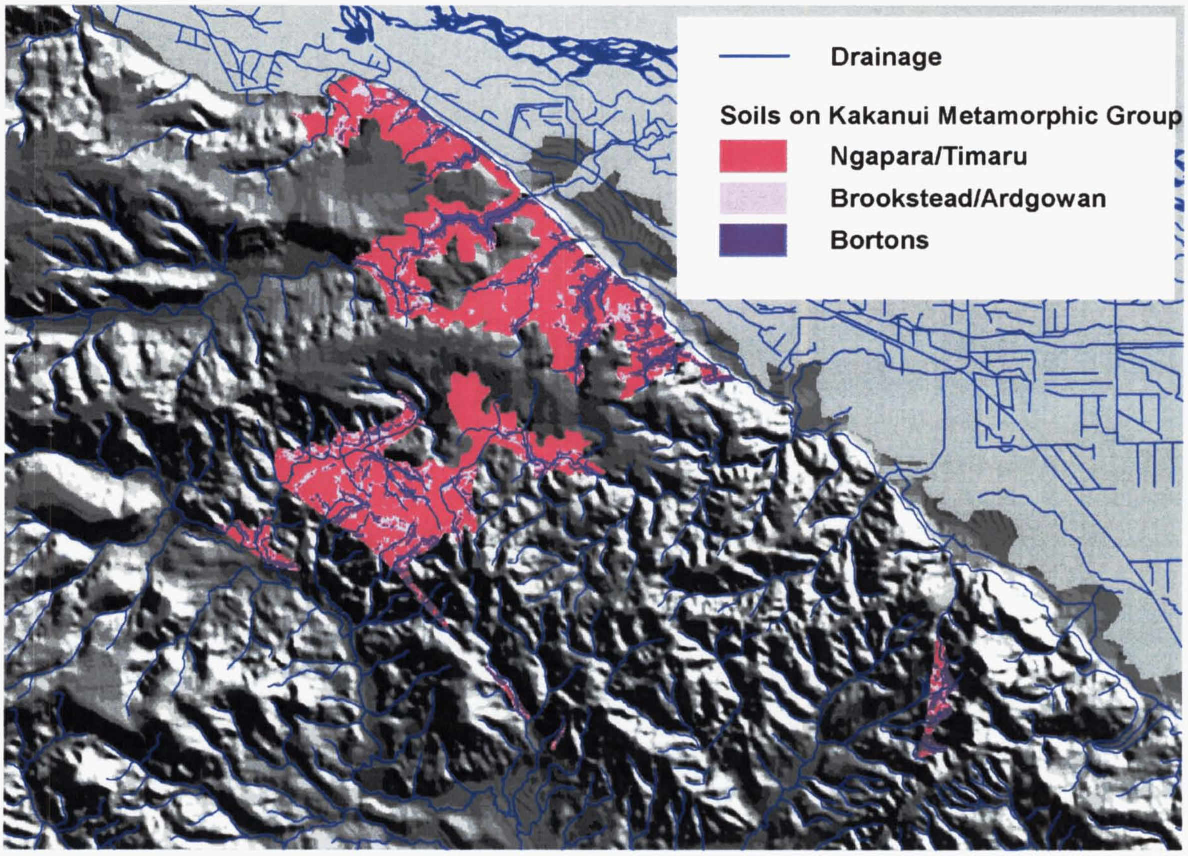


Figure 4.7

Most probable SMUs for Kakanui Metamorphic Group (Gage, 1957).

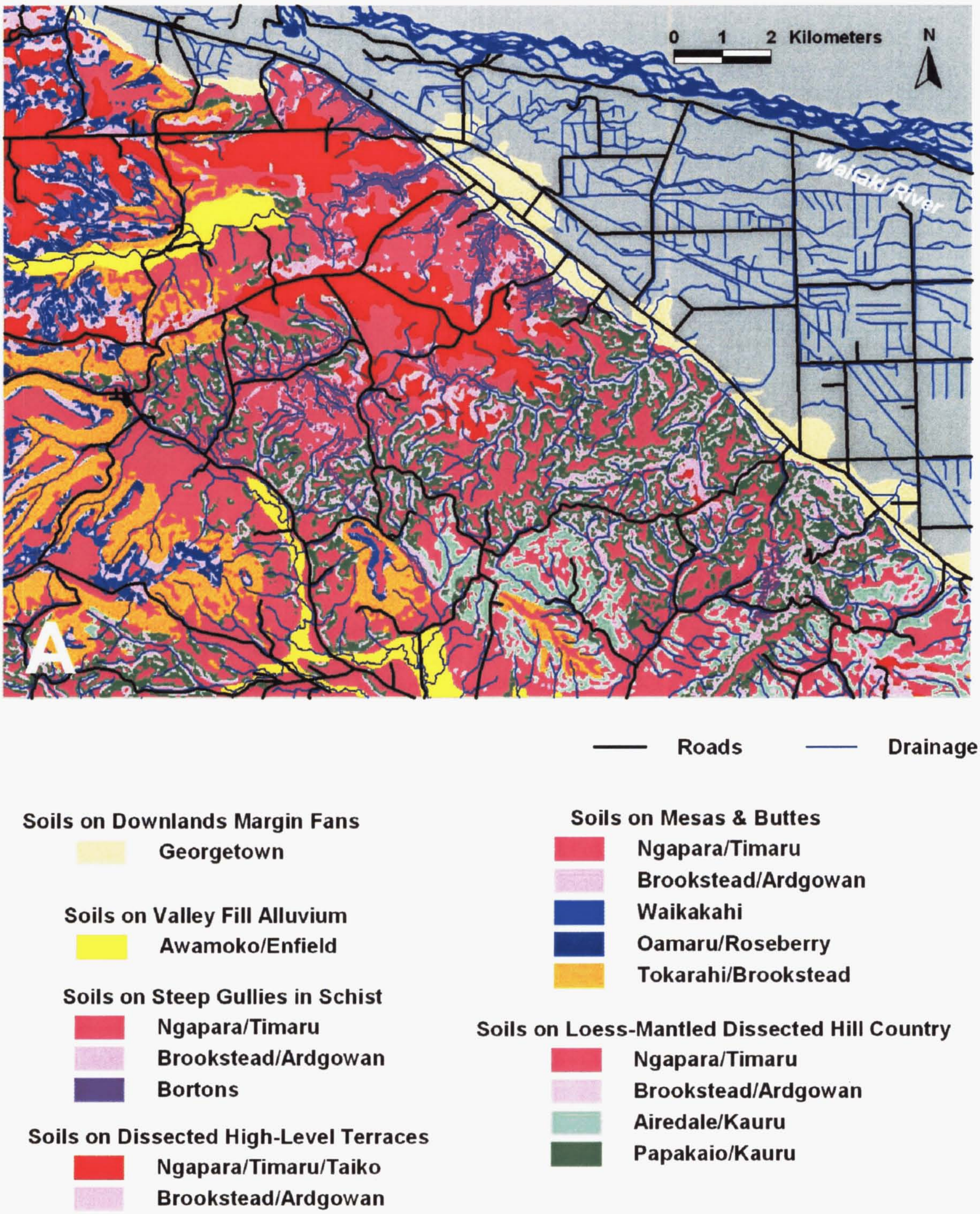
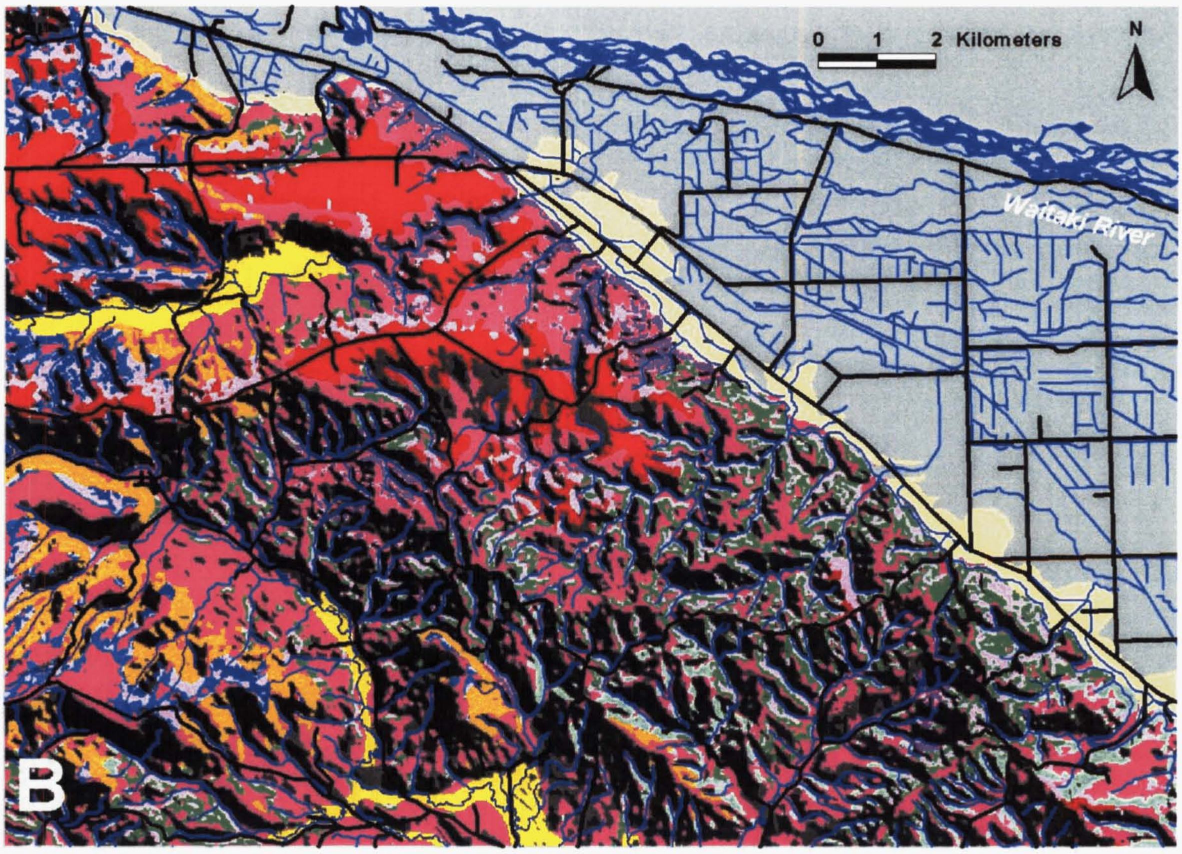


Figure 4.8

A) Soil map of the study area derived from qSLM 1.



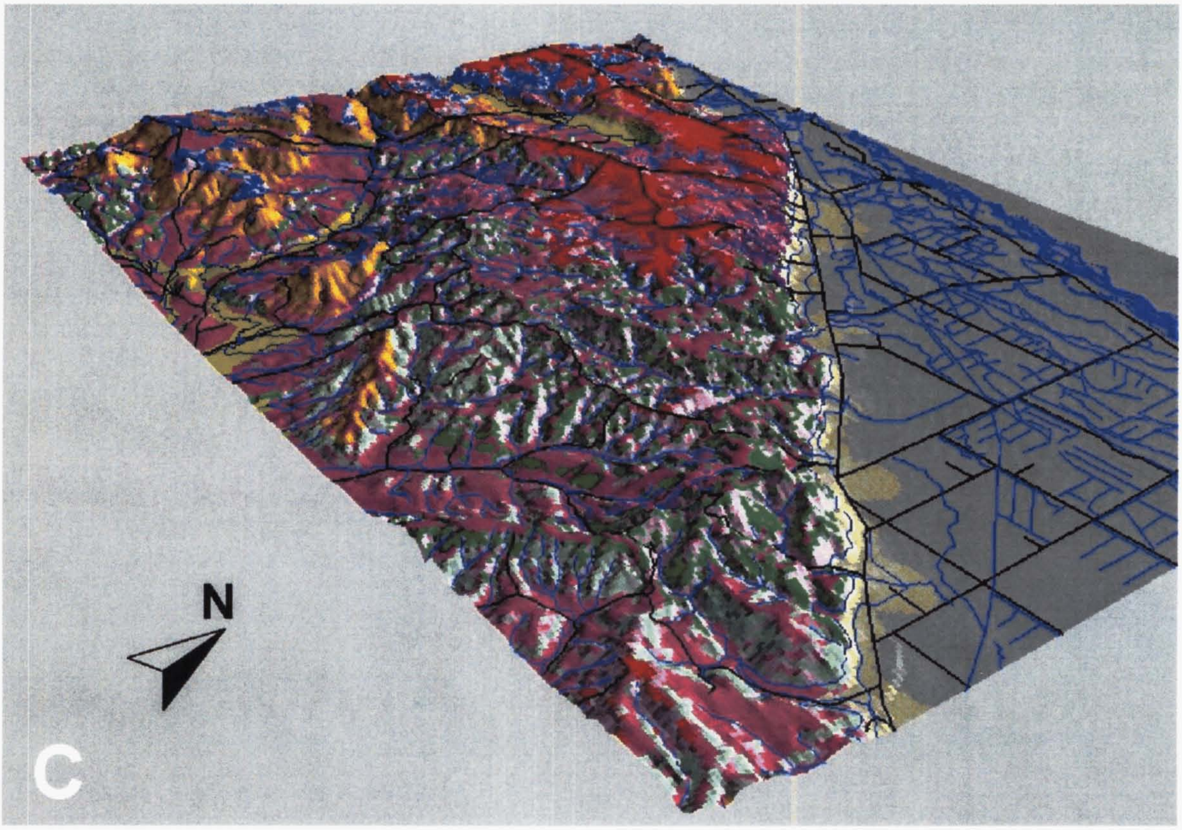


Figure 4.8 continued

B) Soil map of the study area derived from qSLM 1, overlain by a digital shaded relief model illuminated from the northeast. See A (previous page) for legend.

C) 3D perspective of the soil map of the study area derived from qSLM 1, looking northwest. See A (previous page) for legend.

4.2.4 Validation

Quantitative Soil-Landscape Model 1 was validated in two ways: 1) the map produced by qSLM 1 was compared with Wilson's (1970) map (Figure 2.29) to assess similarity in spatial distribution of SMUs and 2) the map produced by qSLM 1 was used to predict the occurrence of STUs observed in the field.

In order to compare qSLM 1 with Wilson's (1970) soil map, a randomised sample of New Zealand Map Grid points coded by Wilson's (1970) SMUs was intersected with qSLM 1 to assess the percentage agreement between the randomised sample and corresponding SMU grid cells in qSLM 1. The results are shown Table 4.3. Mean percentage agreement between Wilson's (1970) SMUs and those of qSLM 1 was 39% (Table 4.3). The highest individual SMU agreements were for Georgetown Soils (93%), Ngapara Soils (71%; 25% on Gravels of the High Terraces and 46% on all other lithological units) and Timaru Soils (62%; 2% on Gravels of the High Terraces and 60% on all other lithological units), reflecting the general similarity with Wilson's (1970) delineation of these SMUs. The remainder of SMUs however show marked differences between maps. This can be explained by the use of Gage's (1957) 1:63,360-scale geological map to define the maximum spatial extent of geological parent material for qSLM 1, and thus a direct comparison with Wilson's (1970) 1:50,000-scale soil map inevitably led to boundary errors, due to the smaller scale and lower resolution of the geological map. Also, where boundary errors were not a factor, Wilson's (1970) lack of rigour in establishing the nature of geological parent materials underlying SMUs (see Section 3.1) led to discrepancies when corresponding points between soil maps were compared. Significant discrepancies also occurred for those soils on colluvial/slopewashed loess parent materials, reflecting a clear difference between Wilson's (1970) depiction of colluvial/slopewashed loess distribution and the colluvial/slopewashed loess distribution predicted from DFA-derived classification functions on each lithological unit (Table 4.2).

Table 4.3

Percentage agreement between Wilson's (1970) SMUs and corresponding SMU grid cells derived from qSLM 1.

% corresponding grid cells in qSLM 1	Samples of Wilson's (1970) SMUs														
	Ng	**Ti**	**Tk**	**Br**	**Ar**	**Aw/Ef**	**Ge**	**Wk**	**Om**	**Rb**	**To**	**Ai**	**Ku**	**Pk**	**Bo**
	n=100	*n=99*	*n=100*	*n=99*	*n=99*	*n=98*	*n=99*	*n=100*	*n=98*	*n=88*	*n=97*	*n=96*	*n=99*	*n=100*	*n=100*
Ng/Ti/Tk	**25**	**2**	**17**	2				33		10	26			29	
Ng/Ti	**46**	**60**	34	28	32	52	3	19	8			42	28		31
Br/Ar	17	13	18	**41**	**26**	7	3	19	27	14	7	25	12	40	33
Aw/Ef		4	1			**38**			1	6	1				
Ge				1	1		**93**	5						2	9
Wk	1	2		1				**8**	3	6	2		1		
Om/Rb			3	2				2	**39**	**34**	4		3		
To/Br	6	3	15	**5**	1	2		10	22	31	44		43		
Ai/Ku		12	3	1	14							**22**	**7**	4	
Pk/Ku	2	3	5	14	25	1	1	4			13	11	**5**	**23**	5
Bo	3	1	4	4							2			2	**22**

Ng = Ngapara
Ti = Timaru
Tk = Taiko
Br = Brookstead
Ar = Ardgowan
Aw/Ef = Awamoko/Enfield
Ge = Georgetown
Wk = Waikakahi
Om = Oamaru
Rb = Roseberry
To = Tokarahi
Ai = Airedale
Ku = Kauru
Pk = Papakaio
Bo = Bortons

In order to assess the predictive ability of qSLM 1, spatial locations of STU-coded field observations (n=164; see Section 3.1) were intersected with qSLM 1 and their correspondence was analysed (Table 4.4). For some STUs sample sizes were too small for meaningful interpretations (*e.g.* Oamaru and Kauru Soils with two and four observations, respectively).

Mean overall correspondence between field-observed STUs and predicted map units in qSLM 1 was 39% (Table 4.4). The highest correspondence was for Georgetown Soils (82%), followed by Timaru Soils (71%) and Awamoko/Enfield Soils (71%). This indicates that Gage's (1957) delineation of valley-fill alluvium and fans of the downlands margin was useful for predicting the occurrence of Georgetown and Awamoko/Enfield Soils, and also reflects the general success of qSLM 1 in predicting the spatial distribution of the primary loess parent materials in the area where Timaru Soils are mapped. Correspondence between Ngapara STUs and predicted map units was lower (54%; 27% on Gravels of the High Terraces and 27% on all other lithological units). Correspondence between Brookstead STUs and predicted map units was also 54% (38% correspondence of the simple mapping unit and 16% on the Tokarahi/Brookstead complex), and correspondence for Ardgowan Soils was 17%. The correspondences between remaining STUs and qSLM 1 SMUs were poor (<50%), and in general reflect the inability of qSLM 1 to successfully predict the spatial occurrence of colluvial/slope-washed loess parent materials, as well as boundary errors resulting from the use of Gage's (1957) lithological units. While the prediction success of some qSLM 1 SMUs was high, the overall prediction success (39%) was worse than that of Wilson's (1970) original soil map (54%, see Section 3.1).

Table 4.4

Percentage agreement between STUs observed in the field and corresponding SMU grid cells derived from qSLM 1.

Corresponding grid cells in qSLM 1	Observed STUs: Ng	Ti	Tk	Br	Ar	Aw/Ef	Ge	Wk	Om	Rb	To	Ai	Ku	Pk	Bo
Ng/Ti/Tk	7		3					1							1
Ng/Ti	7	5	3	3	2	2	1	1			12	3	1	2	1
Br/Ar	3	1	5	5	1		1	2	1	1		1	2	5	2
Aw/Ef	2					5				2	1				
Ge			1	2			9								1
Wk	4		1							1	3				
Om/Rb	2								1	2	5				
To/Br	1		1	2				1		2	11				
Ai/Ku		1	2		2							2			
Pk/Ku					1							1		3	
Bo				1									1		5
N	*n=26*	*n=7*	*n=16*	*n=13*	*n=6*	*n=7*	*n=11*	*n=5*	*n=2*	*n=8*	*n=32*	*n=7*	*n=4*	*n=10*	*n=10*
SMU Predictive Success (%)	54	71	19	54	17	71	82	0	50	25	34	29	0	30	50

Ng = Ngapara
Ti = Timaru
Tk = Taiko
Br = Brookstead
Ar = Ardgowan
Aw/Ef = Awamoko/Enfield
Ge = Georgetown
Wk = Waikakahi
Om = Oamaru
Rb = Roseberry
To = Tokarahi
Ai = Airedale
Ku = Kauru
Pk = Papakaio
Bo = Bortons

4.3 Discussion

4.3.1 The Need for Defining Uncertainty

While the map derived from qSLM 1 may be considered predictive, a significant limitation is the lack of specific probabilities (or uncertainties) assigned to individual soil-coded grid cells indicating the likelihood STU occurrence at those SMU grid cell locations. As stated by Morrison (1990), if discrimination functions are to be used for the classification of future observations, some estimate of their error rates would be essential. It was beyond the scope of the present work to assign probabilities to individual SMU-coded grid cells. However, a brief discussion of potential development of probability-based digital soil maps is presented below.

As discussed in Section 4.2.2, by averaging the discriminant scores for all the observations within a particular STU sample group, group centroids were derived. The centroids for the groups indicated the most typical location in N-dimensional space of any individual from a particular group, and distances between group centroids were a measure of the degree of discrimination along the dimension being tested. Within any group, the distance in N-dimensional space between an individual observation and that observation's group centroid is referred to as the *Mahalanobis squared distance*, or Mahalanobis D^2. The probability that an observation belongs to a group is approximately proportional to the observation's Mahalanobis D^2 distance from the centroid (StatSoft, 2002). Probabilities are conventionally referred to as *probabilities of misclassification*. While an exploration of the mathematics of the probability of misclassification is beyond the scope of the present work it should be noted that, as reviewed by Morrison (1990), a variety of approaches have been used to estimate misclassification probabilities, but no consensus concerning optimal approaches is evident. Despite this, the Mahalanobis D^2 method has been applied to a wide range of conventional and GIS-based ecological research (*e.g.* McLendon and Dahl, 1983; Browning, 2000; Dunn and Duncan, 2000), and is potentially useful in the production of probability-based digital soil maps given suitable training set and validation data.

Cooley and Lohnes (1971, p.234) stated that scientists are required to keep statistical methods subordinated to research problems, and that decisions regarding methods should always be provisional and flexible. While the DFA used in the present work is particularly amenable to exploring the relationships between categorical STU data and numerical digital terrain attribute data, and in establishing associated classification schemes, other methods are also currently in use. In particular, decision trees allow the use of quantitative as well as categorical variables in a dataset, both as explanatory and response variables, and are also capable of generating prediction uncertainty maps of soil data (Bui and Moran, 2001). Other statistical techniques involve discrete and continuous (fuzzy) classification procedures (Irvin *et al.*, 1997; Zhu *et al.*, 2001). It is obvious that a range of statistical analyses can potentially be applied to the modelling of STU data using digital terrain attributes, and that no one technique is best for quantitative soil-landscape modelling. An extension of the present work should utilise those statistical techniques that can most efficiently provide probability/uncertainty data accompanying any digital soil maps produced, be they hardcopy or GIS-based interactive maps.

4.3.2 Considerations on Using Pre-Existing Map Data for Quantitative Soil-Landscape Modelling

The success of the primary objective for developing qSLM 1 – the replication of Wilson's (1970) soil map – is reflected in the percentage agreement among SMUs (39%) between the two (Table 4.3). Given that qSLM 1 was an attempt to replicate the spatial distribution of Wilson's (1970) SMUs along with their inherent impurities, the degree of success is relatively low. The dissimilarity between the two maps is primarily the result of qSLM 1 incorrectly replicating the spatial distribution of loess parent materials, compounded by incorrect spatial distribution of geological parent materials possibly resulting from errors in Gage's (1957) delineation of lithological units and subsequent digitising.

Wilson's (1970) and Gage's (1957) maps were of different scales and accordingly produced boundary errors, which compounded the poor replication results. Even if Gage's (1957) geology map had been the same scale as Wilson's (1970) soil map, inconsistencies in Wilson's (1970) assignment of SMUs to soil-landscape units would have confounded accurate replication. Such inconsistencies are exemplified in Table 4.1, where on the Papakaio Formation, soils on colluvial/slope-washed loess parent materials (Brookstead/Ardgowan Soils) are on steeper slopes (10.7°) than soils on geological parent materials (Papakaio/Kauru Soils – 9.9°). This relationship is in disagreement with Wilson's (1970) own conceptual SLMs (see Section 2.7) and is not consistent with relationships between SMUs and digital terrain attributes on other lithological units (Table 4.1). These inconsistencies propagated through the analysis and contributed to the poor replication of Wilson's (1970) map by qSLM 1.

Despite the relatively poor replication result, the success of qSLM 1 at predicting STUs in the field (also 39%) is only 15% worse than Wilson's (1970) map (54%) and is better than one would expect on the basis of the relatively poor replication of Wilson's (1970) SMUs. It would appear that the imperfections in the quantification of Wilson's (1970) soil-landscape rules are compensated for by the finer grain size of the DEM, and therefore the predictive ability of qSLM1is not as bad as the comparison with Wilson's (1970) map might suggest. Indeed, qSLM 1's prediction of Ngapara and Timaru Soils is more successful than that of Wilson's (1970) map (compare Tables 3.1 and 4.4). On this basis it seems that the use of qSLM 1 for extrapolation of soil data beyond the study area is valid for those soils where prediction success of taxa equalled or exceeded 50% (Ngapara,Timaru, Awamoko/Enfield, Oamaru and Bortons Soils.

From the experience of developing qSLM 1, the following conclusions were reached:

- **In the process of encapsulating Wilson's (1970) map by DFA, information is lost.** DFA as a quantitative tool is unable to capture the range and depth of information represented by more qualitative tacit models of soil landscapes. However, DFA is a potentially useful multivariate statistical technique in discriminating between categorical soil series data on the basis of digital terrain attributes, and appears useful for producing predictive functions with which to construct digital soil maps.

- **Existing geological data are a useful tool for quantitative SLM construction.** Gage's (1957) geological map is useful in delineating soils with geological parent materials, although its 1:63,360-scale introduces boundary errors and is unable to resolve members within formations that are important parent materials.

- **The overall predictive ability of the soil map derived from qSLM 1 is inferior to that of Wilson's (1970) original map.** The original 1:50,000 scale soil map is a better predictor of STUs in the field than is qSLM 1, largely due to the latter's dependence on smaller-scale/lower resolution geological data for the spatial distribution of SMUs.

- **The use of qSLM 1 for the extrapolation of soil data for other areas may be valid depending on the soil series being mapped.** The success of qSLM 1 in predicting STUs is better than that expected based on comparison with Wilson's (1970) map, and the quantitative rules defining the spatial extent of certain soils may be applied outside of the study area.

The following Chapter describes the development of a second SLM based upon data obtained in the field.

Chapter 5

A Quantitative Soil-Landscape Model of the Study Area Based on Field Data

5.1 Introduction

A quantitative SLM of the study area was developed using soil taxonomic unit (STU) data obtained in the field, digital terrain attributes and the pre-existing lithological data of Gage (1957). Since this SLM was the second developed for the present work, it will be referred to as quantitative SLM 2 (qSLM 2). As with qSLM 1 (Chapter 4), qSLM 2 was constructed using DFA to assign DEM grid cells to soil taxa.

5.2 Development of qSLM 2

The major steps involved in the development of qSLM 2 are shown in Figure 5.1.

5.2.1 Sampling & Data Generation

Samples were STU data obtained in the investigation of the purity of Wilson's (1970) SMUs (Section 3.1), and digital data obtained in the same manner as qSLM 1 (Chapter 4). ArcView 3.1 software (ESRI, 1996) was used to intersect randomly generated NZMG points with Wilson's (1970) SMUs so that 10 points fell within each SMU (Figure 3.2a). A Trimble ProXR 12-channel GPS antenna and receiver (Trimble, 2002) was used for field navigation to these points. The slope position of the point was noted, and slope and aspect were measured using compass and clinometer. Soils were investigated by hand auger up to 2 m depth, and horizon thicknesses, root depth, colour, textures and moist and wet consistence were described. Sampled pedons were allocated to STUs (soil series) on the basis of existing series definitions. The spatial locations of sample points were recorded with the ProXR GPS unit, and later differentially corrected by post processing to sub-5 m accuracy. Type sections of pedons are presented in Appendix 2, and descriptions of sample point pedons are shown in Appendix 3.

Corrected GPS data were imported into ArcView GIS software (ESRI, 1996). For the purposes of qSLM 2 analysis all STUs were further grouped according the nature of their parent materials:

- Primary Loess Parent Materials (Ngapara and Timaru Soils)
- Colluvial/Slopewashed Parent Materials (Brookstead and Ardgowan Soils)
- Lithological Parent Materials (Taiko, Waikakahi, Oamaru, Roseberry, Tokarahi, Airedale, Kauru, Papakaio and Bortons Soils)

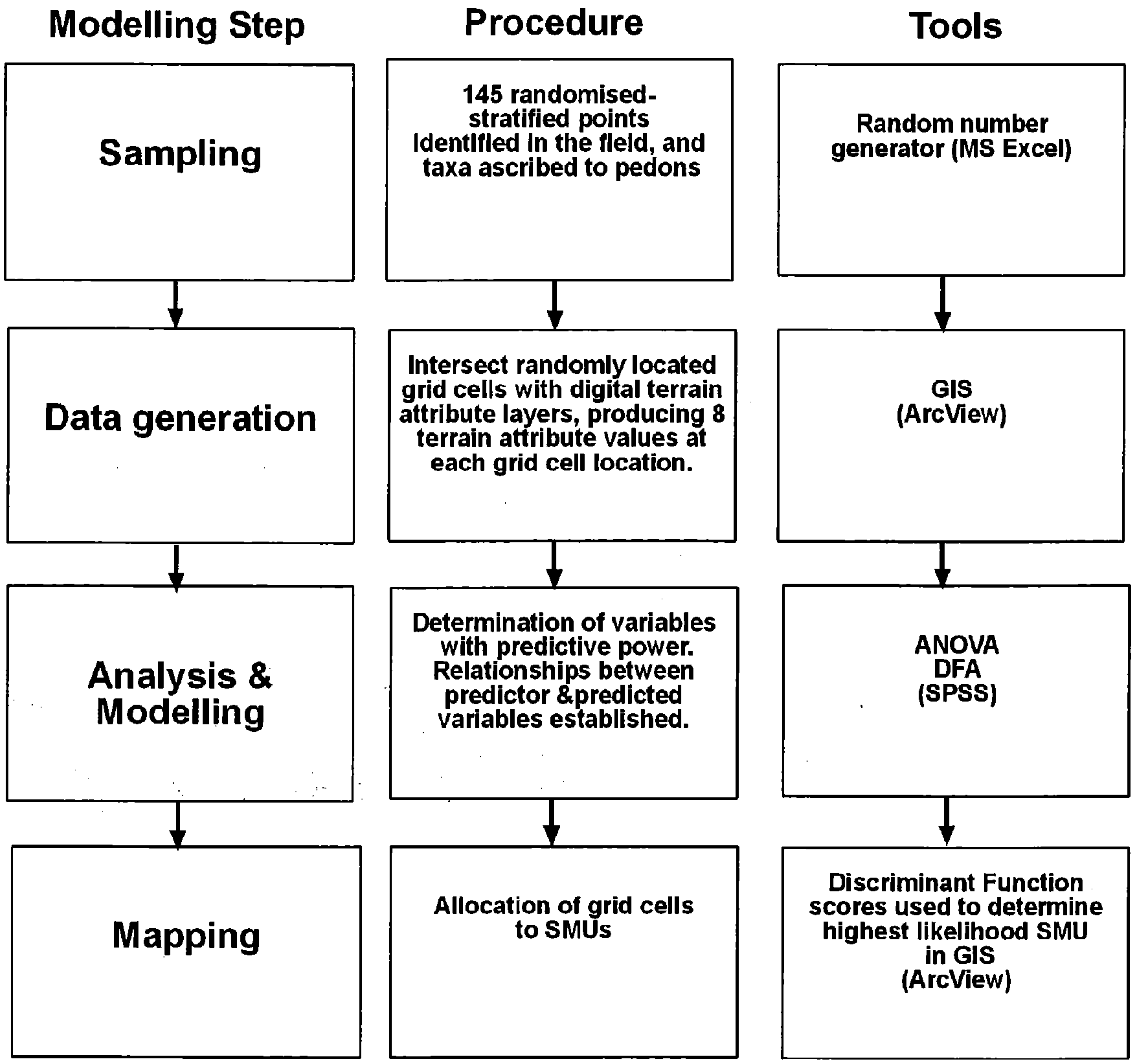


Figure 5.1

The major steps that were undertaken in the development of qSLM 2.

Points falling within the Fans of the Downlands Margin and Quaternary Alluvium physiographic units were excluded, and the spatial distribution of the soils on these units was modelled with conventional digital terrain analysis. The parent material-coded observation points (n=145) were converted to a 25 m grid raster coverage for intersection with the digital terrain attribute grids (Figure 5.2). After the intersection procedure each grid cell, coded for the parent material to which it belonged, had eight digital terrain attributes associated with it. These eight predictor variables were used in the subsequent analysis phase (Figure 5.1).

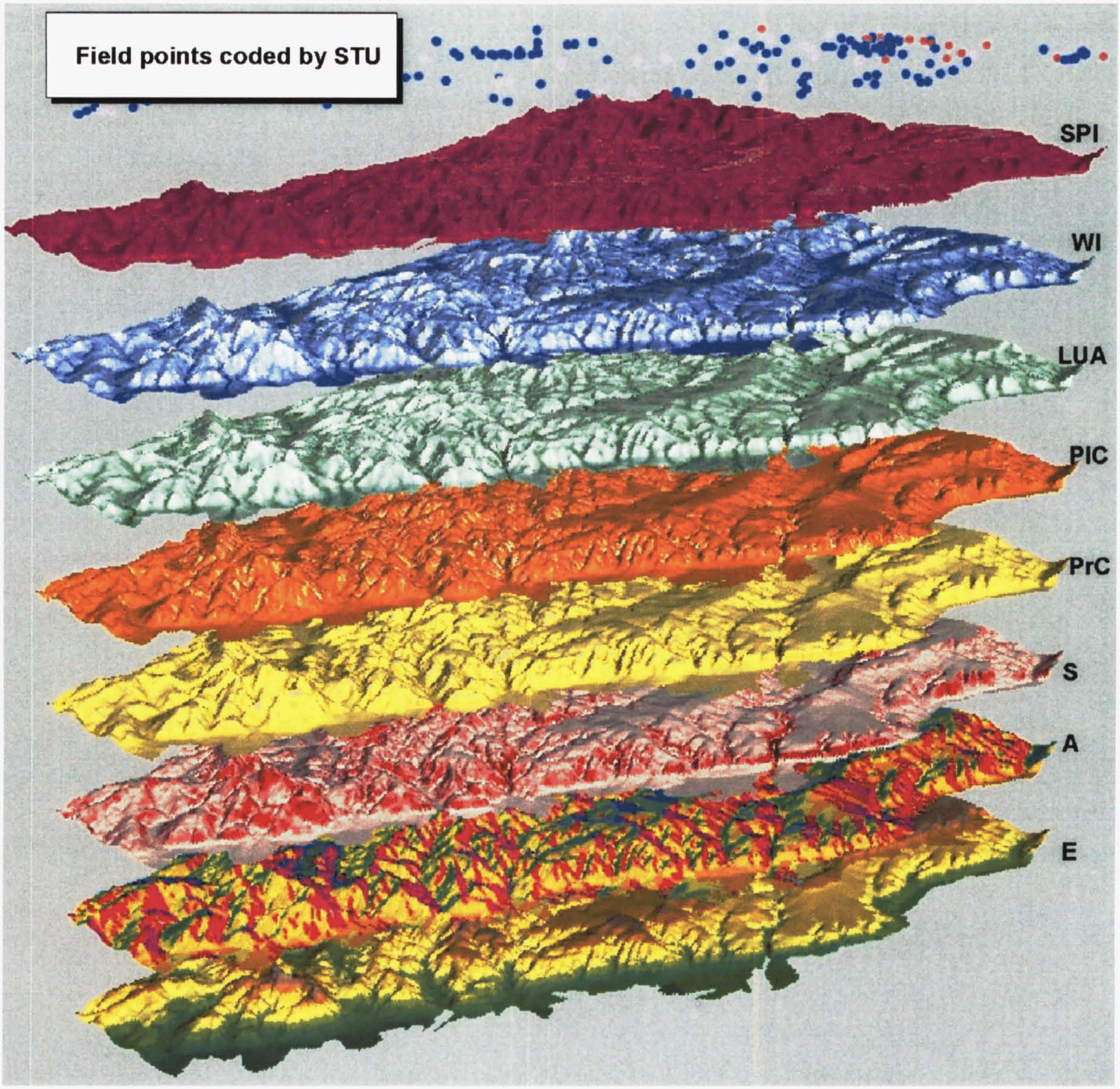


Figure 5.2

Development of the qSLM 2 statistical database using field data obtained for the present study and digital terrain attributes. The field points coded by STU were converted to 25 m grid cells and intersected with all the digital terrain attribute layers within the extent of the study area. The result is each soil-coded grid cell being associated with the digital terrain attributes at that specific grid cell location, and the capture of data amenable to statistical analysis. E = Elevation; A = Aspect; S = Slope; PrC = Profile Curvature; PlC = Plan Curvature; LUA = Log Upslope Area; WI = Wetness Index; SPI = Stream Power Index.

5.2.2 Analysis & Modelling

Statistical analysis was carried out using SPSS 10.0.1 software (SPSS Inc., 1999). Analysis of variance was performed to see if there were statistically significant differences in mean digital terrain attribute values between soil parent materials. DFA was used to generate functions discriminating between parent materials on the basis of digital terrain attribute values.

Two discriminant analyses using digital terrain attributes were conducted for each parent material. In the interests of parsimony, the first discriminant analysis used only those digital terrain attributes that showed significant differences ($P < 0.05$) in mean values between parent materials from the univariate testing. This was a stepwise estimation where the independent digital terrain attribute variables were entered into the DFA one at a time on the basis of their discriminating power. Terrain attribute variables that did not enter the model were either not useful in discriminating between parent materials, or were correlated with variables used earlier in the stepwise analysis and therefore deemed superfluous. Elevation was excluded from the analysis despite showing significant differences between parent materials because this terrain attribute was not considered to be a useful predictor variable outside of the study area. The second analysis was a simultaneous estimation where all independent variables were considered concurrently, so that the discriminant function was computed based on the entire set of variables regardless of the discriminating power of each variable. Therefore all terrain attributes where $P < 0.05$ were used to assess the relative improvement of parent material discrimination over using the stepwise analysis.

Classification functions and classification results for each parent material were derived from the simultaneous analysis. The classification functions were used to allocate grid cells to parent material group by inserting the observation's values for the independent digital terrain attribute variables in the classification function, and a classification score for each parent material was calculated for that observation. The observations were then allocated to the group with the highest classification score.

Slope and Stream Power Index showed significant differences between parent materials (Table 5.1), and mean slope values were in agreement with Wilson's (1970) conceptual SLMs and reflected relationships observed in the field for this study. Mean slope values for Ngapara/Timaru Soils on primary loess parent materials were lower than those for

Table 5.1

Mean and standard deviation of digital terrain attribute values at field sites locations of STUs.

		Mean/ Standard Deviation							
		E	**A**	**S**	**PrC**	**PlC**	**LUA**	**WI**	**SPI**
Primary Loess	**Ng/Ti** *n*=29	213/ 46	157/ 105	4.6/ 3.8	-0.06/ 0.2	0.09/ 0.2	4.3/ 1.2	7.3/ 1.6	-1.5/ 1.2
Colluvial/ Slopewashed Loess	**Br/Ar** *n*=20	181/ 44	137/ 74	9.3/ 4.5	0.1/ 0.3	-0.01/ 0.2	4.9/ 0.8	6.8/ 1.0	-0.4/ 0.6
Lithology	**Tk/Wk/ Om/Rb/ To/Ai/ Ku/Pk/ Bo** *n*=96	177/ 41	163/ 108	10.0/ 6.4	-0.02/ 0.3	-0.02/ 0.2	5.0/ 1.2	7.0/ 1.7	-0.4/ 0.9
	F	**5.1****	**0.6**	**9.9*****	**3.9***	**3.1***	**3.3***	**0.7**	**16.3*****

Digital Terrain Attributes

E = Elevation (m)
A = Aspect (bearing in °)
S = Slope in °
PrC = Profile Curvature
+ve – concave
-ve – convex
PlC = Plan Curvature
+ve – convex
-ve – concave
LUA = Log Upslope Area
WI = Wetness Index
SPI = Stream Power Index

Soil Series & Complexes

Ng/Ti = Ngapara/Timaru
Br/Ar = Brookstead/Ardgowan
Tk = Taiko
Wk = Waikakahi
Om = Oamaru
Rb = Roseberry
To = Tokarahi
Ai = Airedale
Ku = Kauru
Pk = Papakaio
Bo = Bortons

* = $P < 0.05$
** = $P < 0.01$
*** = $P < 0.001$

Brookstead/Ardgowan Soils on colluvial/slopewashed loess parent materials, and soils on lithological parent materials (Pleistocene gravels, Tertiary sediments and Paleozoic Semischist) had the steepest slope values. A physical interpretation of the relationship between STU and DEM-derived slope values would suggest that slope is an important variable in loess accumulation, and hence its spatial variability as a soil parent material. Stream Power Index supports this contention, and points to the importance of slope in determining the power of overland flow (Table 5.1). As slope increases, Stream Power Index becomes more positive, implying that with increasing slope the erosive power of overland flow removes any deposited loess and prevents loess accumulation. The soil-landscape pattern appears to be influenced by the presence or absence of primary and colluvial/slopewashed loess as determined by slope and its influence on overland flow, and where these loess parent materials are absent on the steepest slopes geological parent materials determine the nature of pedons. Profile Curvature, Plan Curvature and Log Upslope Area showed weaker and less significant differences in mean values between parent materials (Table 5.1).

The DFA ascribed discriminant scores to all of the training set grid cells within parent material groups, which were then averaged to derive group centroids. The group centroids indicated the most typical location in N-dimensional space of any individual from a particular group, and distances between group centroids were a measure of the degree of discrimination along the terrain attribute dimension being tested. The group centroids for each parent material are plotted on axes of discrimination in Figure 5.3. Axes on the left show those group centroids calculated from discriminant functions based on stepwise analysis using digital terrain attributes where P < 0.05. Axes on the right show group centroids for the same parent materials calculated from discriminant functions based on simultaneous analysis using digital terrain attributes where P < 0.05, and that were used for modelling and mapping. The farther apart the parent material group centroids, the better they are discriminated from each other.

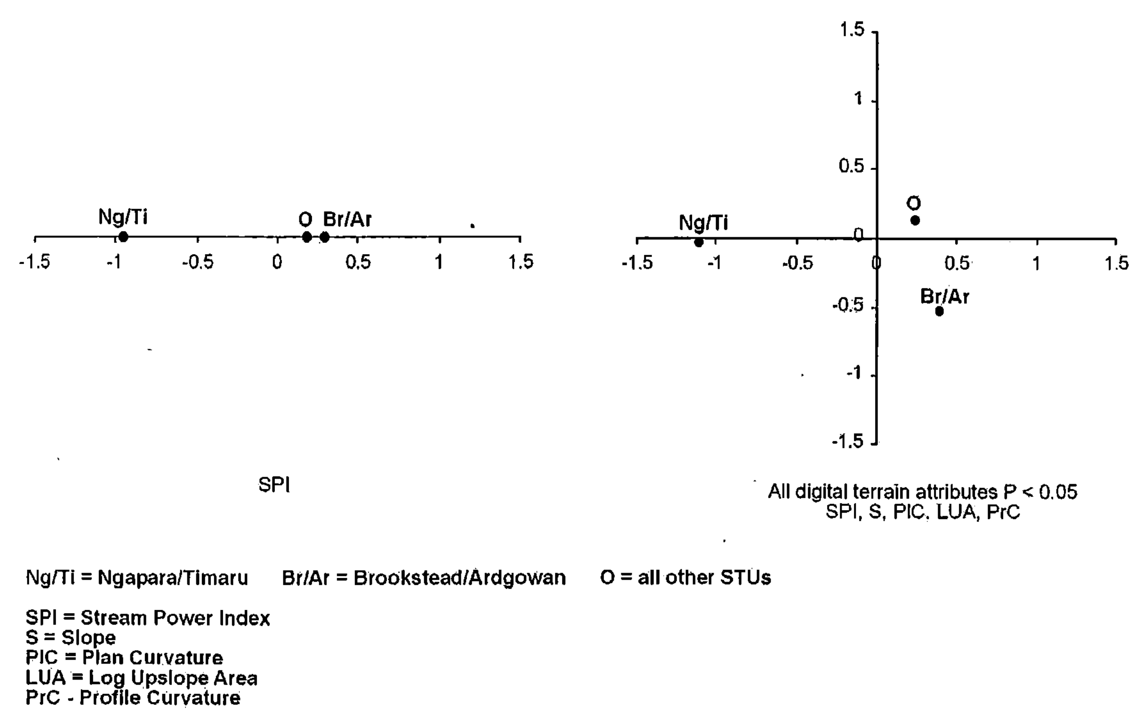


Figure 5.3

Group centroids for STUs calculated from DFA and plotted on discriminant axes. Axis on left shows the centroid functions derived from stepwise analysis using significant univariate predictors. Axes on right show centroids derived from simultaneous DFA using all digital terrain attributes where P < 0.05. These were used in the development of qSLM 2.

Stepwise DFA produced a discriminant function that separated parent material centroids based on Stream Power Index alone (Figure 5.3, axis on left). Ngapara/Timaru Soils on primary loess parent materials were successfully discriminated from Brookstead/Ardgowan Soils on colluvial/slopewashed loess and all other soils on geological parent materials, but there was no discrimination between these latter two. Simultaneous DFA using all digital terrain attributes where $P < 0.05$ (except Elevation) achieved successful discrimination between parent material group centroids (Figure 5.3, axes on right). While this combination of variables is not as parsimonious as that derived in the stepwise DFA, the improved discrimination was used for subsequent modelling and mapping.

Classification functions and success of classification results derived from the simultaneous DFA are shown in Table 5.2. Soils on both primary loess and colluvial/slopewashed loess showed moderate classification success (66% and 67%, respectively), but the combined soils on geological parent materials were generally poorly classified based on digital terrain attributes (43%).

Table 5.2

Classification functions and classification results from discriminant analysis of digital terrain attributes at field observation locations of STUs.

		Classification functions	% of original grouped cases correctly classified
Soil Series & Soil Complexes	**Ng/Ti**	(PlC × 18.605) + (LUA × 7.683) – (SPI × 13.2) + (S × 2.024) – (PrC × 0.811) – 33.357	66
	Br/Ar	(PlC × 17.151) + (LUA × 7.508) – (SPI × 11.547) + (S × 1.961) – (PrC × 2.101) – 30.599	67
	Tk/Wk/Om/Rb/To/Ai/Ku/Pk/Bo	(PlC × 17.055) + (LUA × 7.877) – (SPI × 12.273) + (S × 2.081) – (PrC × 0.03484) – 33.704	43
			Mean = 51%

Soil Series & Complexes

Ng/Ti = Ngapara/Timaru
Br/Ar = Brookstead/Ardgowan
Tk = Taiko
Wk = Waikakahi
Om = Oamaru
Rb = Roseberry
To = Tokarahi
Ai = Airedale
Ku = Kauru
Pk = Papakaio
Bo = Bortons

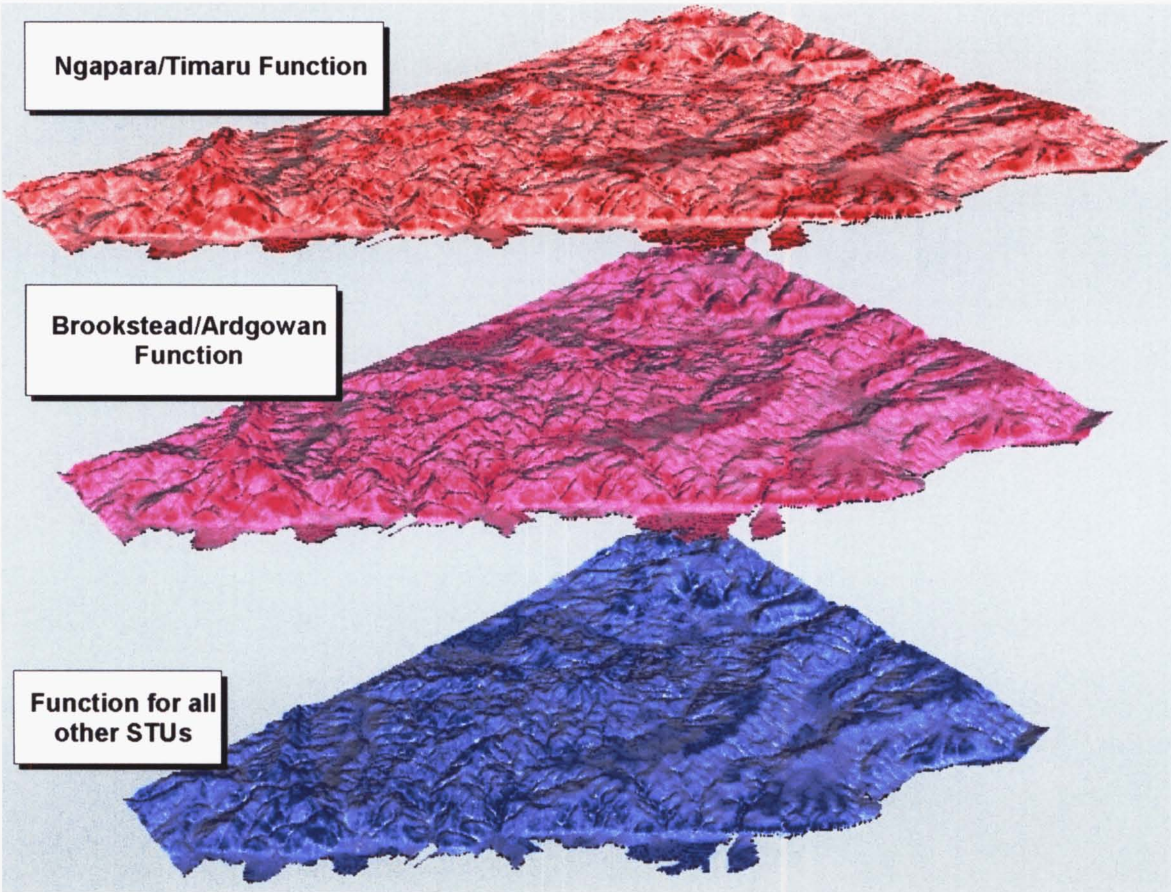
Digital Terrain Attributes (P < 0.05)

PlC = Plan Curvature
LUA = Log Upslope Area
SPI = Stream Power Index
S = Slope
PrC = Profile Curvature

5.2.3 Mapping

The simultaneous discriminant functions described earlier, which form qSLM 2, were used to derive a soil map. Consider the set of discriminant functions that apply to the parent materials (Table 5.2). The scores calculated from the discriminant functions at individual grid cell locations are directly proportional to the probability that the cell belongs to parent materials associated with each discriminant function. Hence, the mapping procedure involved determining the highest discriminant scores for all grid cells and then allocating grid cells to parent material whose discriminant function produced the highest score.

This process is illustrated Figures 5.4 and 5.5. Figure 5.4 shows the discriminant function value ranges for the predicted soils on their respective parent materials, and Figure 5.5 shows those grid cells coded by parent material with the highest discriminant scores. Soil taxa on loess parent materials were automatically ascribed to the appropriate grid cells, which became SMUs. Also shown is the combined SLU for Georgetown/Awamoko/Enfield Soils derived from digital terrain analysis, and constituting all areas on the DEM where local relief is less than 20 m and slope is less than 5°. The spatial coverage of soils on geological parent materials was intersected with Gage's (1957) geological data to ascribe taxa and delineate SMUs (Figure 5.6). Results were combined to produce a final soil map derived from qSLM 2 (Figure 5.7).



Ngapara/Timaru Function	Brookstead/Ardgowan Function	Function for all other STUs
4.121 - 18.873	4.887 - 18.756	4.975 - 19.444
18.873 - 33.625	18.756 - 32.626	19.444 - 33.914
33.625 - 48.378	32.626 - 46.496	33.914 - 48.383
48.378 - 63.13	46.496 - 60.366	48.383 - 62.852
63.13 - 77.882	60.366 - 74.235	62.852 - 77.322
77.882 - 92.634	74.235 - 88.105	77.322 - 91.791
92.634 - 107.387	88.105 - 101.975	91.791 - 106.26
107.387 - 122.139	101.975 - 115.844	106.26 - 120.73
122.139 - 136.891	115.844 - 129.714	120.73 - 135.199

Figure 5.4

Classification function value ranges for each of the STUs derived from field observations.

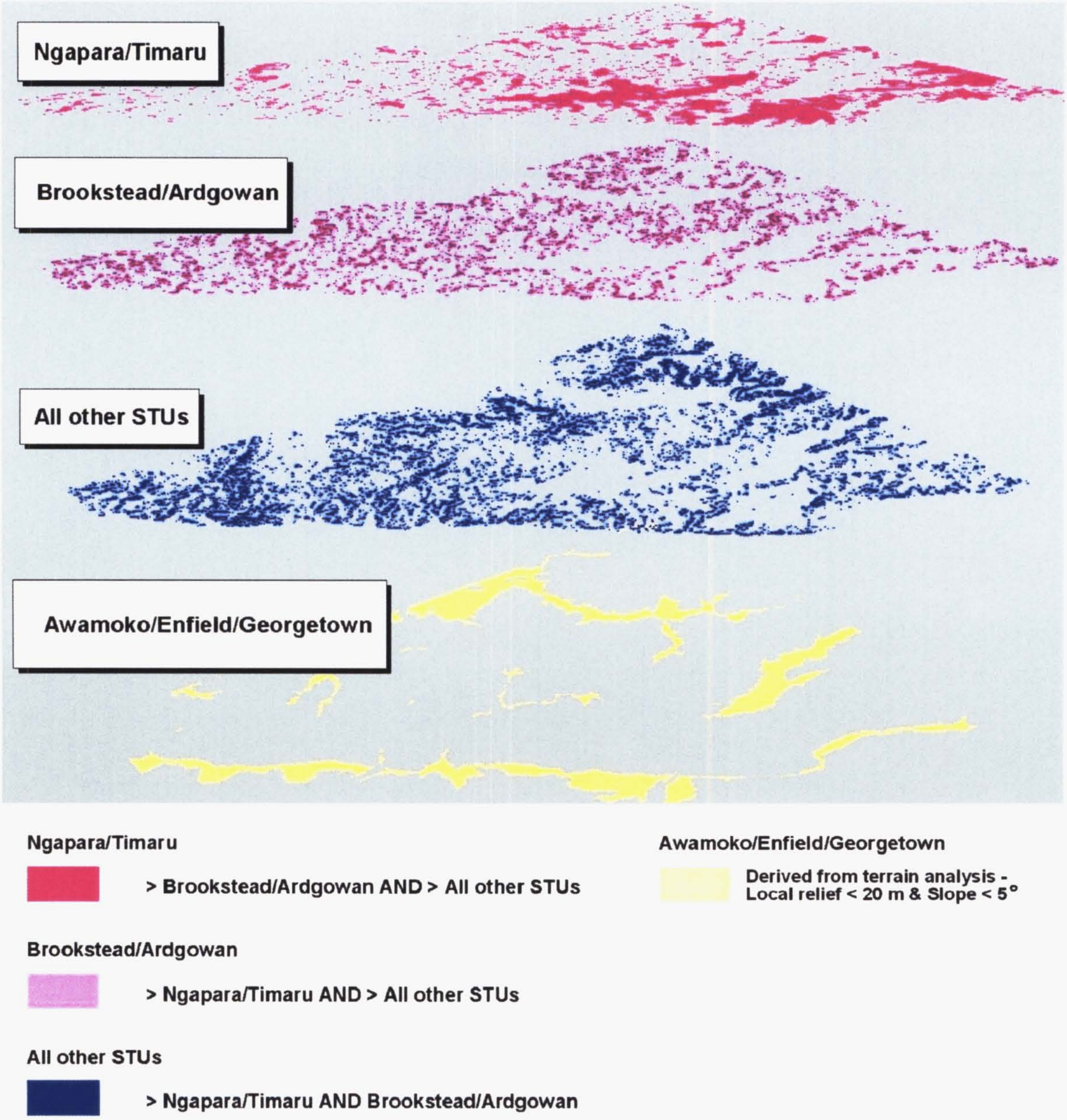


Figure 5.5

Predicted STUs based on the highest classification function value at each individual grid cell location for Ngapara/Timaru, Brookstead/Ardgowan and all other STUs, as well as Awamoko/Enfield/Georgetown derived from terrain analysis.

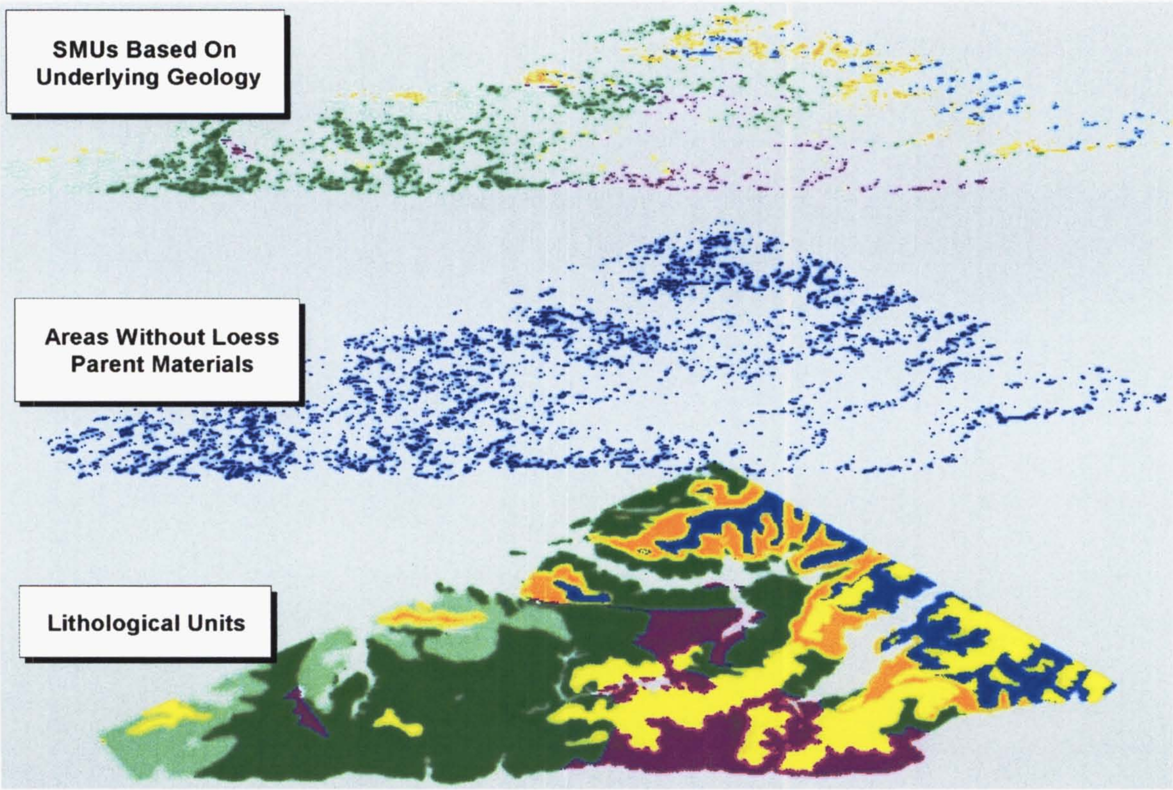


Figure 5.6

In order to ascribe series to soils without loess parent materials, the predicted spatial distribution of these soils was intersected with lithology (from Gage, 1957).

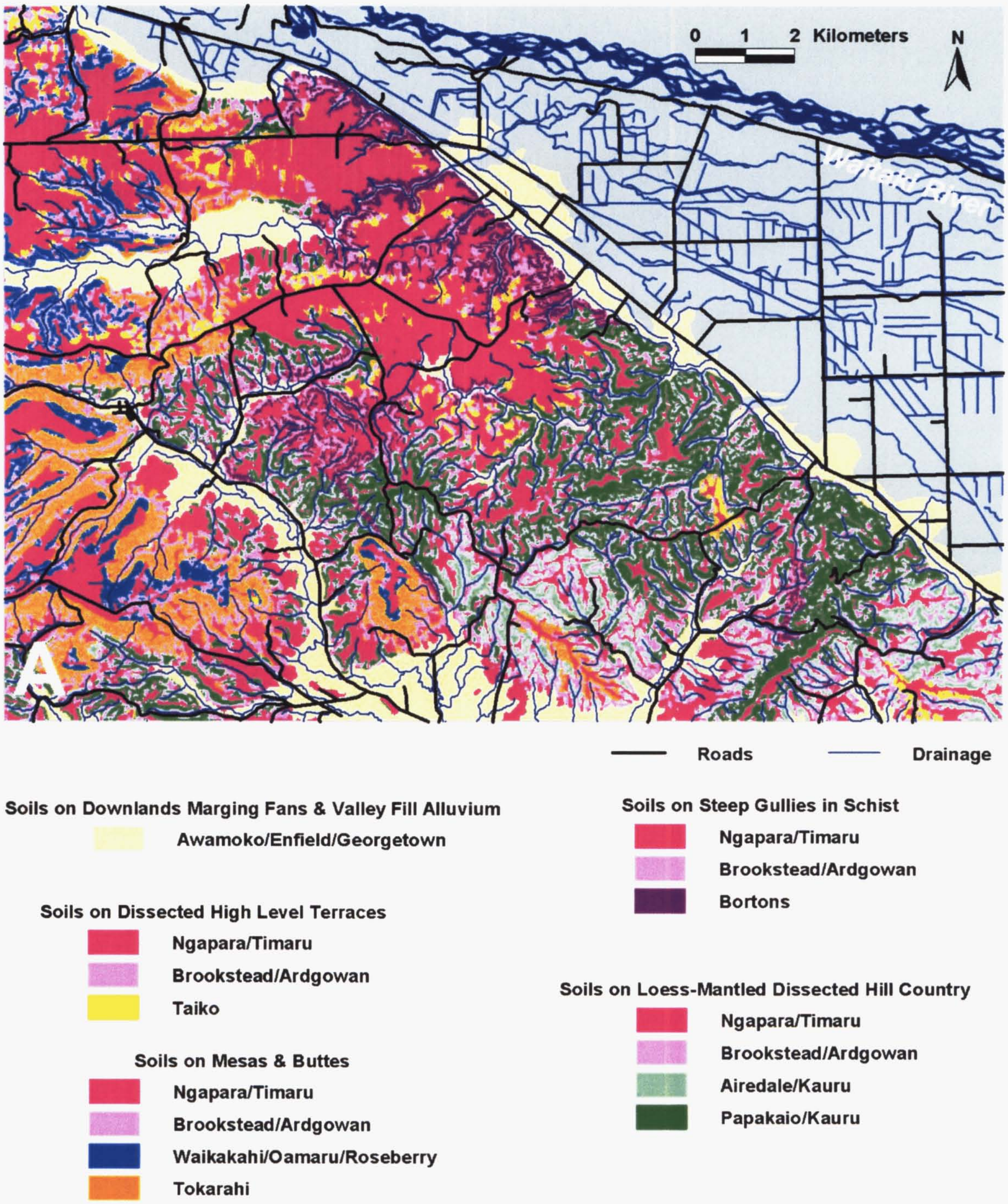


Figure 5.7

A) Soil map of the study area derived from qSLM 2.

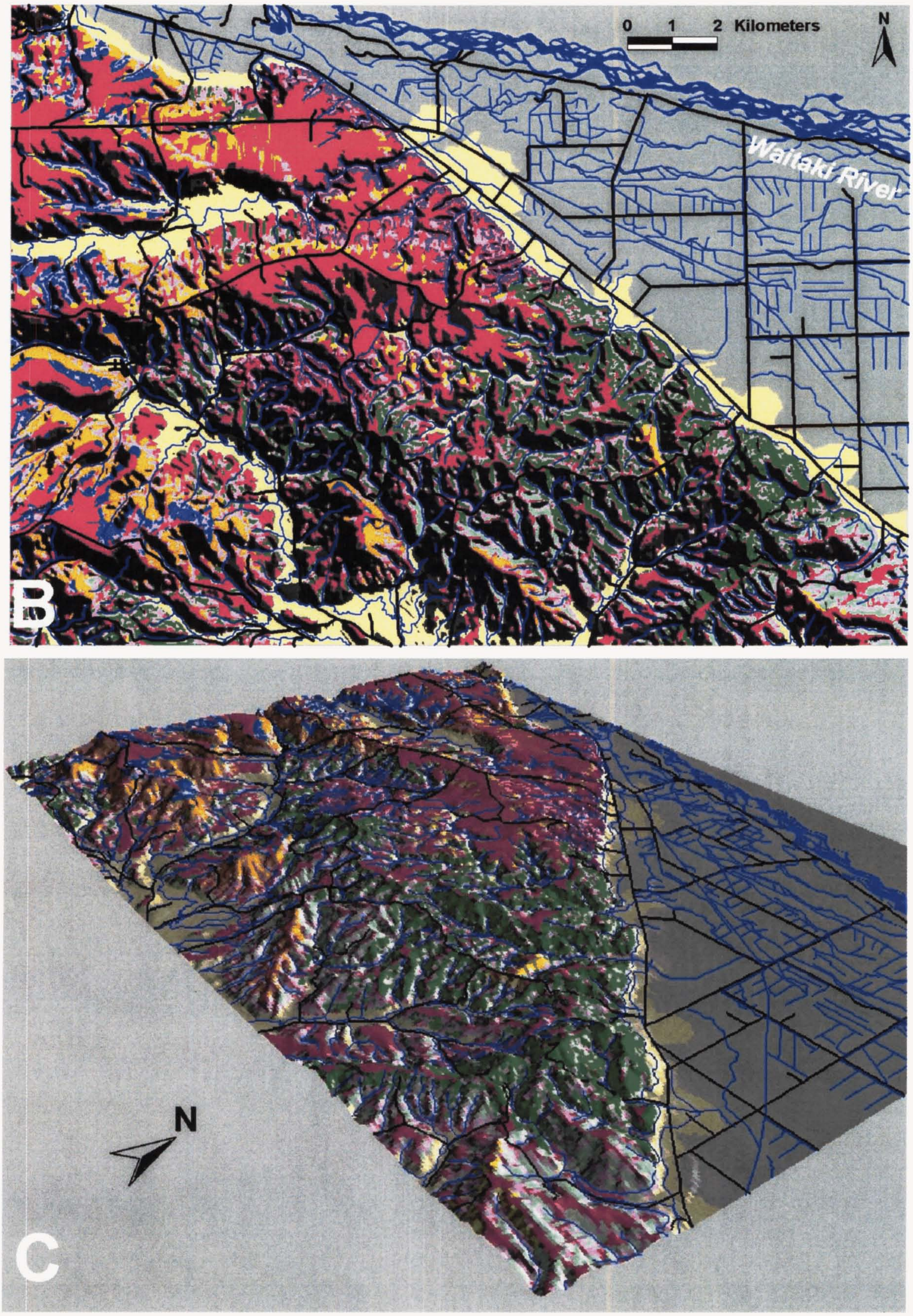


Figure 5.7 continued

B) Soil map of the study area derived from qSLM 2, overlain by a digital shaded relief model illuminated from the northeast. See A (previous page) for legend.

C) 3D perspective of the soil map of the study area derived from qSLM 2, looking northwest. See A (previous page) for legend.

5.3 Discussion

5.3.1 Modelling the Soil Landscape

The limitations of qSLM 2 include not only the quality of the DFA training data, but also limitations in the capacity of the DEM to model the soil landscape. As discussed in Section 1.2.5, the ability of DEMs to accurately represent the land surface is directly related to the original topographic data from which the DEM is derived and the DEM resolution as determined by grid cell size. The significant DEM smoothing of the landscape is evident in Figures 2.25-2.27, and highlights the difficulty in modelling large-scale geomorphic features that may strongly influence the soil-landscape pattern. While the 25 m DEM used in the present work was of sufficient resolution to produce discriminatory variables capable of differentiating between grouped STUs, it was of insufficient resolution to model slope processes involved in loess accumulation/erosion from the underlying geology. To digitally model these processes, high-resolution GPS-based DEMs need to be constructed for representative physiographic regions within the study area.

The DEM used here was also incapable of distinguishing between areas with similar morphometry that have formed in different ways *e.g.* loess-mantled landscapes versus landscapes formed in a loess mantle. In the former, the discontinuous nature and varying thickness of the loess mantle over pre-existing landscapes contributes to the loessial/geological parent material control of the soil pattern. In the latter, all of the landscape's relief is formed into the soil mantle, and loessial parent materials predominate. If landscape morphometry is similar in both types of loess landscape, quantitative rules relating sampled STUs to specific values of slope, curvature and stream power index can be erroneously applied to an incorrect loess landscape. For example, Ardgowan Soils may dominate 10-15° slopes in a landscape formed into a loess mantle, but Taiko Soils may dominate similar slopes in a loess-mantled landscape. Clearly, quantitative rules derived for one loess landscape cannot be validly applied to another, and some means of distinguishing the two is desirable if DEM-based modelling is to be useful in the investigation of terrestrial systems influenced by aeolian sediment.

DEM resolution was also insufficient to model detailed changes in slope that influence the transitions between Roseberry, Oamaru, Waikakahi and Ngapara Soils, and as discussed above, the use of the DEM to model STU distribution did not take into account lithological differences affecting loess accumulation. This was especially the case with the Glauconitic

Sandstones and Greensands lithological unit and to a lesser extent the Otekaike Limestone, where on flat surfaces (as defined by the DEM) Tokarahi and Waikakahi Soils were present and not the expected Ngapara/Timaru Soils. In addition, the boundary errors inherent in Gage's (1957) geological data made the use of these data problematic and were of concern mainly in the relatively restricted areas of transition between lithological units.

Despite the limitations of digital terrain attribute data and geological data in modelling the soil landscape, and qSLM 2 mirrored landform components and appeared realistic. Ngapara/Timaru Soils on primary loess parent materials were in general correctly assigned to flat areas on uplifted terraces and interfluves, and Brookstead/Ardgowan Soils were mapped on both shoulder- and foot-slope positions. All other soils on Pleistocene gravels, Tertiary sediments and Paleozoic semischists were mapped on the steepest slopes. It is clear that the DFA has highlighted relationships between pedons identified in the field and digital terrain predictor variables. The realism of qSLM 2 is due its 25 m cell grain size, and the ability to model and represent both discontinuities between lithological units and the patchiness of loess parent materials in a semicontinuous manner.

5.3.2 The Need for Validation & Defining Uncertainty

Comparison with Wilson's (1970) map was not considered valid because the two mapping approaches operate at much different resolutions of landform. Wilson's (1970) SMUs comprised areas of at least several hectares, whereas the fundamental mapping units of qSLM 2 are 25 m DEM grid cells, resulting in very different map grain sizes (McBratney, 1998). Direct comparisons are therefore not meaningful.

All relevant field data were used in the development of qSLM 2, and as such there was no independent validation data set. qSLM 2 is therefore untested, and its validation will require additional spatially referenced STU data obtained in the field. The map derived from qSLM 2 (Figure 5.7) can serve as a useful tool for designing future validation exercises. As stated in Section 4.3.1, however, while Figure 5.7 may be considered predictive, a significant limitation is the lack of specific probabilities (or uncertainties) assigned to individual soil-coded grid cells. The reader is referred to Section 4.3.1 for a discussion on overcoming this limitation.

5.4 Conclusions

From the development of qSLM 2, the following conclusions can be drawn:

- **Geo-referenced sample point locations are essential.** This is the case not only to place field pedology on a more scientific foundation concerning repeatability and verification, but also to successfully incorporate these sample locations into the GIS environment for correlation with digital terrain attributes and spatial analysis.

- **DEMs are useful tools for quantitative soil-landscape modelling.** The nature of DEMs means that they can depict the spatial distribution of soils in a semicontinuous manner, and depending on the resolution (grid cell size) can depict various scales of landform resulting in realistic depictions of soil landscapes. DEMs can be used to model both the polygonal nature of geological parent materials as well as the more continuous nature of loessial parent materials.

- **Discriminant Function Analysis was generally successful in producing quantitative soil-landscape rules.** The ability of DFA to differentiate between categorical STU groups on the basis of numerical digital terrain attributes in a way that reflected the situation in nature suggests that this statistical technique is useful for modelling soil series.

- **More detailed geological data are required.** While it is acknowledged that Gage's (1957) geological map is the largest-scale data available and was essential for modelling soil series complexes with geological parent materials, it is of insufficient resolution to depict the lithological variations necessary to represent individual soil series within the Kauru and Papakaio Formations.

- **More pedological field data are required.** Additional data are necessary both for the validation of the DFA-based quantitative SLM presented here and for the development of more sophisticated models, perhaps utilising other statistical methods. Additional data are essential for better modelling the spatial distribution of loess, which profoundly influences the soil pattern in the study area. The use of qSLM2 for extrapolation outside of the study area is not recommended before further testing and validation is carried out.

5.5 Directions for Future Research

Wilson (1970) developed his map at the 1:50,000 scale for use in land management decision making, with particular emphasis on the nutrient status and soil hydrology of phases within soil series. The development of qSLM 2 has been an attempt to develop an independent map of these soil series, using Wilson's (1970) own series definitions in doing so. However, despite the criticisms able to be levelled at the relatively subjective and unverifiable nature of Wilson's (1970) map, it is still able to depict individual soil series with a much greater reliability than qSLM 2. In order to achieve the kind of map resolution desired for appropriate land management support using the general methods described in this Chapter, the following suggestions are presented for future research:

- **Detailed digital terrain analysis and DEM construction.** Terrain analysis should be undertaken with emphasis on the identification of distinct physiographic regions within the study area characterised by similar slopes, curvatures and drainage network densities. Within each delineated physiographic region representative areas encompassing slope- and catchment-scale landforms should be modelled with high-resolution GPS-based DEMs. These high resolution DEMs can be used for subsequent modelling of soil types.

- **Improved soil survey.** Within the selectively modelled areas in different physiographic regions, intensive geo-referenced soil data need to be collected to characterise the soil pattern, which can then be predictively applied to the remainder of the physiographic region. Density of observations should be sufficient to allow modelling of soil types and properties at a range of scales, and to allow modelling of loess distribution. Successive predictive maps should be repeatedly tested, with validation data subsequently incorporated into more sophisticated quantitative SLMs.

- **Re-mapping of geology.** The geology of North Otago is an important predictor of soil series and associated physical and chemical properties in those areas where loess is thin or absent. The geology of the study area should be re-mapped at a scale sufficient to resolve lithological units with distinct differences in fabric, texture and mineralogical/chemical composition. This lithological map would be invaluable in defining the spatial extent of geological parent materials.

The feasibility of the above suggestions is of course dependent on both time and money. In addition, decisions must be made as to whether future research should be focused on soil-series based STUs and SMUs, or focused on more quantitatively defined soil properties instead. As discussed in Section 1.2.5, pedological research has for some time been concerned with using DEM and GIS technologies to model continuous soil properties, at a range of spatial and temporal scales, that are of direct relevance to land management and understanding landscape processes. In the context of the present work two such properties – A horizon total organic carbon and total organic nitrogen – are discussed in the next Chapter.

Chapter 6

Carbon & Nitrogen Analysis

6.1 Introduction

Quantitative Soil-Landscape Model 1 (Chapter 4) and qSLM 2 (Chapter 5) are models describing the spatial distribution of conceptual classes – SMUs and STUs – using quantitative terrain attributes. STUs and SMUs group together similar pedons and areas of land (on the basis of STU content), respectively. They give an acceptable portrayal of spatial variability of soil properties, particularly those used to define the STUs. However, as a model of spatial variability of accessory properties (*e.g.* % carbon and % nitrogen), this approach can be found wanting, depending on the correlation between STUs or SMUs and the accessory property (see Adams and Wilde, 1978). The present chapter presents an exploratory analysis of the spatial variability of A horizon carbon (C) and nitrogen (N) in relation to STUs, parent materials, terrain attributes and microclimate data.

Carbon and N are essential components of soil organic matter and are involved in important biogeochemical cycles. Knowledge of C and N dynamics is important for the elucidation of landscape and ecological processes and for the practical management of soils for primary production in a sustainable manner, with organic matter C in particular an important component of soil fertility and quality. In addition, soils constitute the largest terrestrial reservoir of C (Post *et al.*, 1982; Gessler *et al.* 2000) and therefore play a significant, if poorly understood, role in global CO_2 sinks and production. An understanding of the spatial distribution and dynamics of C is therefore beneficial for identifying fundamental processes operating over a range of spatial and temporal scales, as well as contributing to sustainable resource use.

It has long been established that the physical and chemical properties of soil parent materials can influence amounts of soil organic matter (Walker and Adams, 1958), and the present analysis investigates the influence of loessial and geological parent materials on A horizon percent organic C and N. Samples were taken from A horizons of sites used to determine the purity of Wilson's (1970) SMUs (Section 3.1) and to develop qSLM 2 (Chapter 5), and this sample scheme was used to test differences in C and N between STUs/parent materials. Modern pedogeomorphic research has established the validity of using DEM and GIS technologies to model the spatial distribution of soil properties (Moore *et al.*, 1993; Gessler *et al.*, 1995; Gessler *et al.*, 1996; Gessler *et al.*, 2000; Yoo *et al.*, 2001), and therefore relationships between A horizon percent organic C, A horizon percent total N, and digital terrain attributes were tested to investigate the influences of landscape position and process. Relationships between C and N and microclimate data (lowest summer rainfall) were also investigated to investigate possible influences of precipitation on soil organic matter contents.

6.2 Methods

6.2.1 Sample Collection, C & N Analysis

At pedon investigation sites (see Figure 3.1a) a 15 cm length, 2.5 cm diameter core probe was used to retrieve ten A horizon samples taken randomly from an area within ~10 m of the auger hole, and samples were then bulked.

Bulked samples were air dried at 25°C for two days, then crushed and passed through a 2 mm sieve. Total C and N were determined from a 0.5 g subsample of the <2 mm soil fraction using a LECO CNS-2000 Elemental Analyser, and A horizon percent C and N were calculated. For most samples total C was considered an accurate estimate of organic C. For soils on CO_3-rich sediments a correction was performed to account for CO_3-derived C (see Section 6.2.3 below).

6.2.2 Digital Data Generation

Sample point locations, logged using a Trimble Pathfinder Pro XR 12-channel GPS antenna and receiver (Trimble, 2002), were differentially corrected in post processing to sub-5 m accuracy and imported into ArcView GIS software (ESRI, 1996). Point location data were converted to a 25 m raster grid, so as to be compatible with digital terrain attribute grids (Section 3.3), then intersected with those grids. The resulting attribute table showed the eight digital terrain attribute values at the sample point locations. Point location data were also intersected with the lowest summer rainfall grid (from NIWA, see Figure 2.4). These data were exported to a spreadsheet in which sample point-coded digital terrain data were associated with appropriate C and N values in preparation for statistical analysis.

6.2.3 Statistical Analysis

Statistical analysis was carried out using SPSS 10.0.1 software (SPSS Inc., 1999). Nitrogen values were linearly regressed against C values, which highlighted outlier C:N ratios for some soils on CO_3-rich parent materials. A second linear regression of C and N was performed that excluded data points on CO_3-rich parent materials. The linear regression function was used to calculate a %C value for the samples formed on CO_3-rich parent materials from the %N values, which were unaffected by soil carbonate. Seven data points were adjusted, with a drop in %C values ranging 0.08-1.03%.

Analysis of variance was performed to test if 1) there were significant differences of %C and %N between soil series within parent material classes and 2) to test if %C and %N differed significantly among parent materials. Percent C and N were also linearly regressed against individual digital terrain attributes and lowest summer rainfall data to investigate possible predictive relationships.

6.3 Results

A horizon percent C is a strong predictor of A horizon percent N (Figure 6.1). This result supports research that clearly shows relatively consistent C:N ratios in soil organic matter (Walker and Adams, 1958).

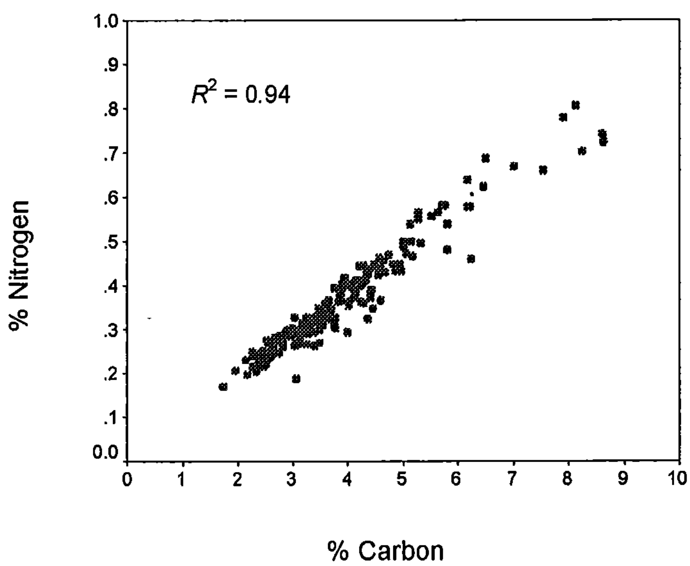


Figure 6.1

Linear regression plot showing relationship between A Horizon percent carbon and A Horizon percent nitrogen.

For parent materials with more than one soil series present (loess, Quaternary alluvium, Otekaike Limestone, Kauru and Papakaio Formations) there were no significant differences in mean percent C and N values between taxa. However, there were significant differences in both mean percent C and N values and C:N ratios between parent materials (Table 6.1). Tables 6.2 and 6.3 indicate whether an individual parent material's mean %C and %N value, respectively, was higher or lower than other parent materials. Mean %C and %N values on Otekaike Limestone were consistently higher than all other parent materials, with values on the Kakanui Metamorphic Group and Glauconitic Sediments and Greensands also showing generally higher values than other quartz- and feldspar-rich loessial and geological parent materials. Although mean C and N values are significant, the classification of parent materials explained only 24% variance in C values and 29% variance in N values.

Linear regression of C and N values against digital terrain attributes resulted in poor relationships. The best relationship for C was with Stream Power Index (Figure 6.2), although this variable explained only 6% of total variance. For N values plan curvature, and Stream Power Index explained only 5% of total variance. Linear regression of C and N values against lowest summer rainfall also resulted in poor relationships (Figure 6.4), with only 4% and 5% of total variance in C and N, respectively, explained by precipitation data.

Table 6.1

Mean A horizon percent C, percent N and C:N values for soil parent materials. Differences between mean values are significant at the P < 0.001 level.

Parent Material	Soil Series Present	A Horizon % C	A Horizon % N	A Horizon C:N
		Mean/ Standard Deviation		
Primary & Colluvial/Slopewashed Loess n=53	**Ng/Ti/Br/Ar**	3.4/ 0.9	0.3/ 0.1	10.8/ 0.8
Quaternary Alluvium n=18	**Aw/Ef/Ge**	2.8/ 0.7	0.3/ 0.1	9.9/ 0.6
Gravels of the High Terraces n=16	**Tk**	3.8/ 0.7	0.4/ 0.1	10.6/ 0.5
Otekaike Limestone n=25	**Wk/Om/Rb/Tt**	5.0/ 1.5	0.5/ 0.1	10.0/ 0.4
Glauconitic Sediments & Greensands n=33	**To**	4.3/ 1.0	0.4/ 0.1	10.7/ 1.1
Kauru & Papakaio Formations n=20	**Ku/Ai/Pk**	3.5/ 1.0	0.3/ 0.2	11.3/ 1.0
Kakanui Metamorphic Group n=10	**Bo**	4.5/ 2.3	0.4/ 0.1	10.7/ 0.7
N = 175	**F**	**10.1**	**12.6**	**7.1**

Ng/Ti/Br/Ar = Ngapara/Timaru/Brookstead/Ardgowan
Aw/Ef/Ge = Awamoko/Enfield/Georgetown
Tk = Taiko
Wk/Om/Rb/Tt = Waikakahi/Oamaru/Roseberry/Taitapu
To = Tokarahi
Ku/Ai/Pk = Kauru/Airedale/Papakaio
Bo = Bortons

Table 6.2

Matrix showing mean C values for individual parent materials higher (+) or lower (-) than other parent materials. * = mean differences significant at the P < 0.05 level.

	Parent Material						
Parent Material	**Loess**	**Quaternary Alluvium**	**Gravels of the High Terraces**	**Otekaike Limestone**	**Glauconitic Sediments & Greensands**	**Kauru & Papakaio Formations**	**Kakanui Metamorphic Group**
Loess							
Quaternary Alluvium	- *						
Gravels of the High Terraces	+	+ *					
Otekaike Limestone	+ *	+ *	+ *				
Glauconitic Sediments & Greensands	+ *	+ *	+	- *			
Kauru & Papakaio Formations	+	+	-	- *	- *		
Kakanui Metamorphic Group	+ *	+ *	+	-	+	+ *	

Table 6.3

Matrix showing mean N values for individual parent materials higher (+) or lower (-) than other parent materials. * = mean differences significant at the P < 0.05 level.

	Parent Material						
Parent Material	**Loess**	**Quaternary Alluvium**	**Gravels of the High Terraces**	**Otekaike Limestone**	**Glauconitic Sediments & Greensands**	**Kauru & Papakaio Formations**	**Kakanui Metamorphic Group**
Loess							
Quaternary Alluvium	-						
Gravels of the High Terraces	+	+ *					
Otekaike Limestone	+ *	+ *	+ *				
Glauconitic Sediments & Greensands	+ *	+ *	+	- *			
Kauru & Papakaio Formations	-	+	-	- *	- *		
Kakanui Metamorphic Group	+ *	+ *	+	- *	+	+ *	

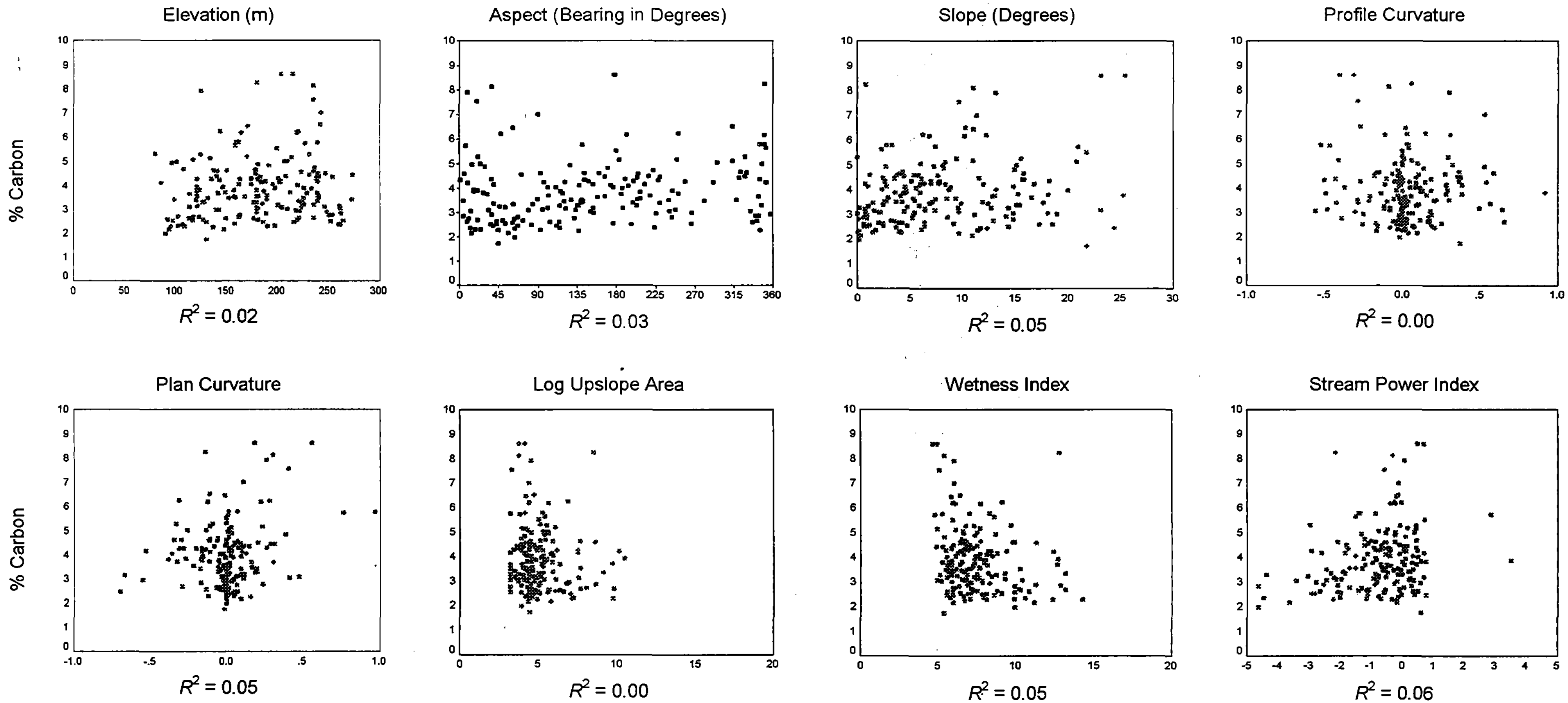


Figure 6.2

Linear regression plots showing relationships between A horizon percent carbon and digital terrain attributes.

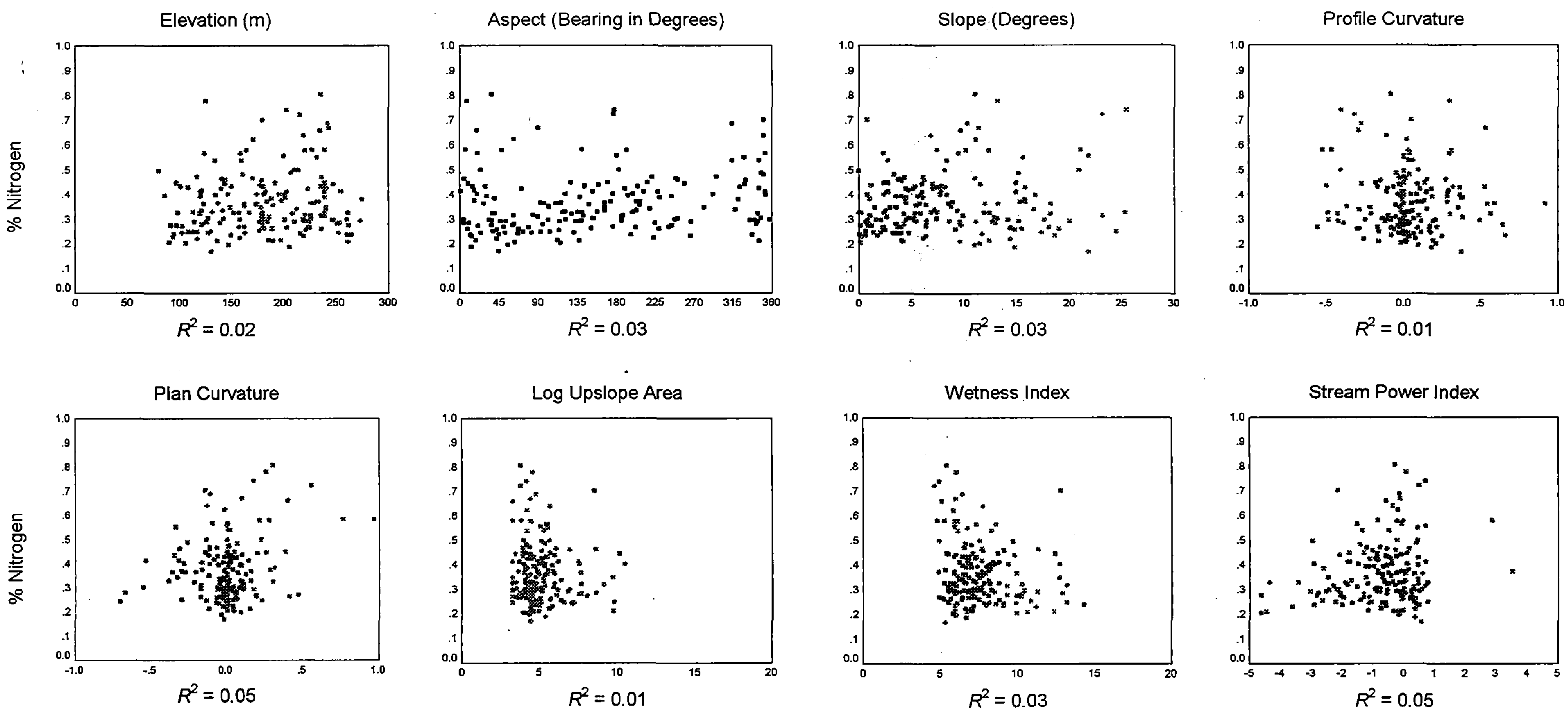


Figure 6.3

Linear regression plots showing relationships between A horizon percent nitrogen and digital terrain attributes.

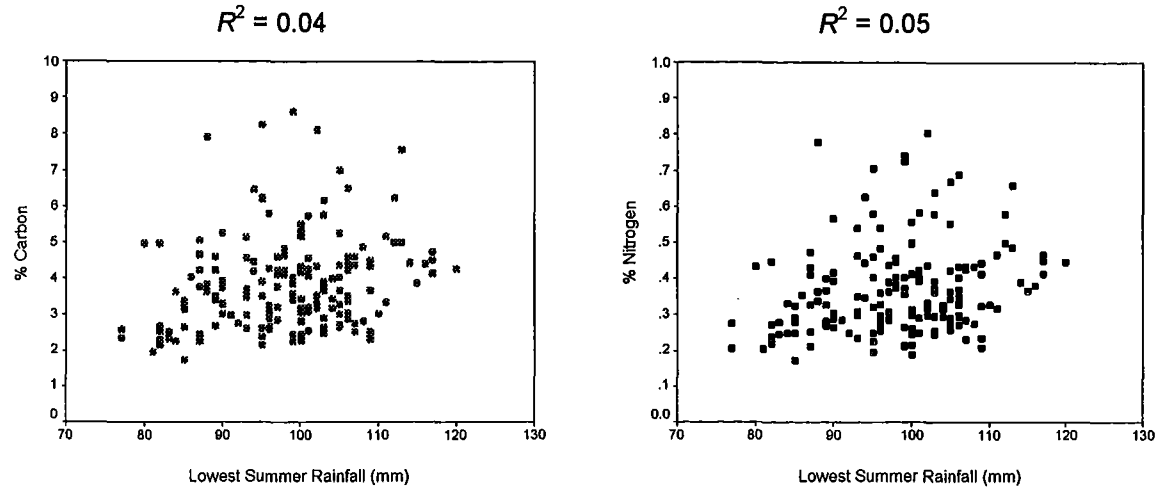


Figure 6.4

Linear regression plots showing relationships between A horizon percent C (left) and A horizon percent N (right) and lowest summer rainfall data for the study area.

6.4 Discussion

6.4.1 Carbon, Nitrogen & Parent Materials

An important caveat must be placed on the interpretation of the influence of parent materials on C and N in the study area: the sampling scheme was not designed to specifically test these relationships. The sampling scheme was designed to investigate the validity of Wilson's (1970) SMUs, and therefore was not intended to elucidate relationships between the physical and chemical nature of parent materials and soil organic matter.

Walker and Adams (1958) highlighted another, more general problem: in any study of parent materials as a factor influencing soil properties all other soil forming factors must be kept constant. Despite the study area being restricted to a single part of the North Otago downlands, there is slight variation in both temperature and rainfall depending on elevation (Figures 2.3 and 2.4). Also, as determined in the field, sample sites were located on a range of slopes with different erodibility characteristics and sites were undoubtedly on a range of different aged soils. This site-specific variation was not captured by digital terrain data however, and the results of C and N values regressed against microclimate and terrain data reflect this (see next section).

Another potential problem is the effects of land use and management on soil organic matter, and the potential these have in masking any parent material signature on amounts of C and N. Sample sites were mostly located on pastoral and dairy farming land, with a minority of samples taken from cropping fields, exotic forestry and unused areas of gorse and scrub, and no historical data concerning fertiliser application and stocking rates were available to assist with interpretation. Despite these apparent complications, the review by Metherell (2002) on the effects of long term increases in farm productivity on soil organic matter emphasised that these changes do not necessarily result in increased C storage, and in some cases soil C content decreased. These studies indicate that despite a range of pasture management treatments including effects of fertiliser, irrigation and stocking intensity, soil C content can remain relatively stable over long periods. For this reason the effects of land use were ignored in the interpretation of parent material influence on C and N values.

In an important paper by Walker and Adams (1958), it was established that in clearly defined conditions the phosphorus (P) content of parent materials was a major factor governing the accumulation of soil organic matter, and that other things being equal parent materials rich in P gave rise to soils containing higher levels of organic matter than P-poor parent materials. Walker and Adams' (1958) analyses showed that while variable, the P content of limestone far exceeded that of greywacke, greywacke-derived loess and various igneous rocks in Canterbury, and that these high P levels were paralleled by high C and N values. This relationship is also shown in the study area, with A horizon C and N values being highest on Otekaike Limestone and lower on Quaternary quartzofeldspathic loess, greywacke alluvium and other Tertiary sediments (Tables 6.1 – 6.3). Walker and Adams (1958) also showed that C:N ratios were lowest where soils were P-rich on limestone parent materials. The range of C:N values in the study area is not great however, and while mean differences are statistically significant, low F ratios indicate that they are not strong (Table 6.1). Nevertheless, the A horizon C:N ratio on Otekaike Limestone is second lowest, and may hint at the role high P content in limestone plays in increased soil C turnover and subsequent lower ratios to N.

A horizon C and N values are also relatively high on Glauconitic Sediments and Greensands and the Kakanui Metamorphic Group. While the former is certainly calcareous and has a high P content, the latter is metamorphosed greywacke and is probably low in P. In the absence of detailed chemical data from these parent materials, it is difficult to surmise on the role played by P and other nutrients on C and N content. However, other studies have illustrated the importance of aluminium in soil organic matter stabilisation. Percival *et al.* (2000) showed that a combination of pyrophosphate-extractable aluminium and allophane content explained the greatest amount of variation in soil C content over a range of New Zealand soils.

Although differences in mean C and N values between parent materials were significant, parent material classification explained only 24% variance in C values and 29% variance in N values. Other possible contributing factors to the remaining variance may include terrain attributes operating at large scales and influences possible localised effects of land management practices.

6.4.2 Carbon, Nitrogen, Digital Terrain Attributes & Microclimate

The poor relationships between A horizon percent C, A horizon percent N and digital terrain attributes can be attributed to one significant problem: the sampling scheme, as with investigating the influences of parent materials, was not designed to specifically test these relationships. Similar studies by others (*e.g.* Moore *et al.*, 1993; Gessler *et al.*, 1995; Gessler *et al.*, 1996; Gessler *et al.*, 2000; Yoo *et al.*, 2001) were designed to test catenary relationships on individual slopes or within small catchments, and therefore were able to incorporate a significant range of explanatory terrain attribute variables. Importantly, these catenary-scale studies were readily amenable to spatial analysis and were able to model the spatial variability of soil properties on contiguous slope systems.

The present analysis, however, was based upon explanatory terrain attribute variables taken from widely separated sites and with no more than one C and N sample coming from any one slope system. Moreover, even if sampling had been designed to investigate catenary-scale C and N spatial variability, the 25 m DEM used here was of insufficient resolution to successfully test such hypotheses by using digital terrain attributes as explanatory variables. Essentially, landscape processes affecting C and N variability are occurring at a scale not detected by the DEM. Figures 6.2 and 6.3 are illustrative of the limitations of a sampling strategy designed for one purpose being used for another. While the sampling strategy did highlight differences in mean C and N values between parent materials (see above), attempts to determine meaningful influences of landscape position (elevation, aspect) and process (slope, profile and plan curvature, upslope area, wetness and stream power indices) on C and N values were unsuccessful. It is suggested here that given appropriate sampling schemes and sufficient high-resolution digital terrain data, such catenary influences will be elucidated. Gessler (1996) has suggested that a DEM grid cell size of 10 m or less is probably necessary to successfully model both terrain characteristics and soil properties.

Lowest summer rainfall also appears to have no influence on A horizon C and N, but as described above, this result could be attributed to a sampling scheme inappropriate for testing such relationships. In addition, the microclimate data used here is preliminary and based upon interpolation between climate station sites, and as such may not capture fine-scale microclimatic variation possibly influencing C and N. As with terrain analysis, appropriate sampling schemes and sufficient high-resolution microclimate data may resolve relationships between soil organic matter and temperature, precipitation and soil moisture deficit.

6.5 Conclusions

From analysis of A horizon percent C, percent N, C:N ratio and digital terrain attributes, the following conclusions can be drawn:

- **Parent material mineralogical/chemical composition influences C and N content.** Calcareous lithologies with high inherent nutrient status show higher topsoil percent C and N than inherently nutrient-poor siliceous/quartzose lithologies, and they also have relatively low C:N ratios.

- **% C and N are poorly correlated with digital terrain attributes and microclimate data.** Digital terrain attributes based on 25 m DEM data are not useful predictor variables for topsoil percent C and N with the sampling pattern used, nor is lowest summer rainfall data.

- **Collection of catena- and catchment-scale data is necessary to realistically model landscape dynamics and spatial distribution of C and N.** High-resolution DEMs and a sampling strategy determined according to landform characteristics should be used to model soil phenomena at a range of scales relevant to processes affecting topsoil C and N content.

6.6 Directions for Future Research

As digital spatial technologies advance, the ability to model biogeochemical cycling in terrestrial ecosystems will improve. This is of importance to precision agriculture, quantitative modelling of pedological phenomena and landscape evolution, and in modelling C and N dynamics at local and regional scales. In order to develop realistic SLMs of C and N the following suggestions are presented for future research:

- **Detailed digital terrain analysis and DEM construction.** Terrain analysis should be undertaken with emphasis on the identification of distinct physiographic regions within the study area characterised by similar slopes, curvatures and drainage network densities. Within each delineated physiographic region representative areas encompassing slope- and catchment-scale landforms should be modelled with high-resolution GPS- or LIDAR-based DEMs. These high resolution DEMs can be used for generating a suite of predictor terrain attribute variables. High-resolution terrain data can then be used for subsequent modelling of soil properties.

- **Collection of soil physical and chemical data.** Sampling strategies need to be devised for collection of relevant soil physical and chemical data. Sampling schemes and densities should be designed so that soil properties can be modelled at a range of scales.

- **Application of a range of mathematical tools.** Quantitative modelling of C, N and other soil physical and chemical properties should be based on a range of mathematical tools such as linear regression analyses used here, regression trees, conditional probabilities, as well as conventional geostatistical analysis.

- **Detailed modelling of spatial distribution of soil parent materials and microclimate data.** The geology and loess of North Otago are important predictors of soil type in the study area and their inherent nutrient status. The combination of these data with high-resolution terrain models will provide more comprehensive models that would better explain C and N values than terrain attributes alone. The geology of the study area should be re-mapped at a scale sufficient to resolve lithological units with distinct differences in fabric, texture and mineralogical/chemical composition. In addition, detailed microclimatic data should be collected and spatially modelled to ascertain relationships between these variables and C and N.

- **Influences of land use at paddock and farm scales must eventually be incorporated into models.** Human influence on biogeochemical cycling in agro-ecosystems must be incorporated into landscape models to account for short-range C and N variation.

As with the development of detailed quantitative SLMs of soil series (Section 5.5), the feasibility of the above suggestions is of course dependent on both time and money. Resources should be directed to research programmes that target specific scales and soil properties of relevance to land managers. As emphasised by Bouma (2001) such projects present opportunities to extend research to other scales, and to investigate processes of importance to both human utilisation of soil resources and human understanding of fundamental Earth Surface System dynamics.

Chapter 7

Summary & Synthesis

Presented below is a summary of the rationale, methodology, findings and significance of quantitative soil-landscape modelling carried out in part of North Otago, South Island, New Zealand.

7.1 Modelling the Soils of North Otago.

Soils can be considered the archetype of a complex Earth Surface System where order is manifest at certain spatial and temporal scales. Understanding of soil landscapes is encapsulated by the soil-landscape paradigm that is the legacy of both the state-factor model and more scientific pedogeomorphological approaches. Traditional approaches to modelling soil landscapes have depended on conventional soil survey and depiction of soil data on chloropleth maps, which have been criticised as being unscientific and unrealistic. Global Positioning System, Geographic Information System and Digital Elevation Model technologies, in combination with appropriate pedogeomorphic variables, can be used to model soil landscapes in a more scientific and realistic manner by using quantitatively defined terrain attributes as predictor variables for soil types and properties.

The GrowOtago project is a regional government initiative to stimulate regional development through identifying new options for primary production in the Otago region. The project involves detailed microclimate modelling and quantitative soil-landscape modelling to produce land resource information. Up to this point in time, Wilson's (1970) soil maps have been the highest-resolution soil data available for North Otago. However, they cover only part of the downlands area. A key aspect of the present work was to attempt to replicate Wilson's (1970) maps and develop strategies for automated soil mapping of the downlands, extending beyond areas already mapped. From the perspective of pedological science, this presented an opportunity to test the validity of Wilson's (1970) SLMs and maps as well as developing separate SLMs that were quantitative and testable, two key criteria for scientific validity.

The soil pattern of the North Otago downlands is dominantly influenced by parent material exposure. There are two elements to this: 1) preservation of a loess blanket (primary and secondary) and 2) exposure of different lithologies. Where loess accumulation has exceeded more than ~ 1 m, either as primary loess deposited on flat surfaces or colluvial/slopewashed deposited on shoulder and footslope positions, it constitutes the parent material and largely controls soil physical and chemical properties. One significant influence is that of loess textural variation with the development of dense, poorly structured fragipans in finer loess resulting in perch-gley subsoil features. Where loess is thinner than ~ 1 m, soils are defined by geological parent materials that influence their physical and chemical nature. Soils with geological parent materials display a range of inherent nutrient and physical properties depending on the texture and mineralogical composition of particular lithological units. The pattern of exposure of different lithological units is controlled by the stratigraphic order of a generally flat-lying sequence of sedimentary rocks and the development of an erosional topography. Faulting in a few locations has a distinct influence on surface exposure of lithologies.

This spatial variation in soil properties is of great importance to primary production. As such, the conceptual SLMs and 1:50,000 scale soil map developed by Wilson (1970), used soil series-based SMUs that summarised the overall physical and chemical nature of Soil Landscape Units. Also included were brief descriptions of soils' susceptibility to water stress and erosion. Wilson's (1970) soil data were intended to assist in land management decision-making, although the extent to which this objective was met is unknown. With the advent of the GrowOtago project, the issue of producing high-resolution soil maps of relevance to land managers is again being addressed through the development of quantitative soil-landscape models.

7.2 The Quantitative Soil-Landscape Models

Presented below is a summary of soil-landscape model development used in this study.

1) Development of a quantitative soil-landscape model to replicate the mapping rules used for the 1:50,000-scale soil map of Wilson (1970; qSLM 1).

- **Pre-existing map data were used as the basis for quantitatively modelling soil resources.** Quantitative Soil-Landscape Model 1 was an attempt to quantitatively define Wilson's (1970) conceptual soil-landscape models in order to automatically produce soil maps of unmapped areas. The lithological data of Gage (1957) and digital terrain attribute data were also used in the construction of qSLM 1.

- **Methodology.** Analysis of variance and Discriminant Function Analysis (DFA) were applied to a randomised sample (n=100) of grid cells within each Soil Mapping Unit (SMU) on separate lithological units. Terrain attributes derived from a 25 m DEM (elevation, aspect, slope, profile and plan curvature, wetness and stream power indices) for each cell were used as predictor variables in both statistical analyses. Both stepwise and simultaneous DFA were performed. In the former analysis, independent digital terrain attributes were entered into the DFA one at a time on the basis of their discriminatory power, which produced a parsimonious combination of predictor variables. In the latter analysis all variables were entered into the DFA simultaneously.

- **Results.** For all lithological units there were significant differences in mean values of slope and stream power index terrain attributes ($P < 0.001$), although the relative magnitudes of mean values were not always consistent with the conceptual SLMs of Wilson (1970) and soil-landscape relationships observed in the field. For the stepwise DFA, slope, profile curvature and stream power index were the most useful terrain attributes for discrimination between SMUs. Success of stepwise DFA-derived classification functions ranged 39-56% among lithological units, suggesting relatively poor overall discrimination. Success of simultaneous DFA-derived classification functions ranged 49-65%. Stepwise DFA functions were used for subsequent mapping due to their more parsimonious use of predictor variables.

- **Mapping and Validation.** The mapping procedure consisted of allocating 25 m grid cells to SMUs on the basis of the highest discriminant function score calculated from the discriminant functions associated with each SMU. Validation of qSLM 1 was done in two ways: 1) comparison with Wilson's (1970) map to assess similarity in spatial distribution of SMUs and 2) comparison of predicted SMUs with STUs observed at 164 locations in the study area. Correspondence between predicted SMUs of qSLM 1 and Wilson's (1970) map was 39% averaged across all SMUs (range 8-93%). Mean overall prediction success of STU prediction was also 39% (range 0-82%)

- **Conclusions.** While qSLM 1's overall success at replicating Wilson's (1970) map was relatively low, its success at predicting soil taxa in the field was better than that expected based on the quality of map replication. This is probably due to the 25 m grain size of qSLM 1 compensating for the deficiencies in capturing Wilson's (1970) original soil mapping rules. Some of Wilson's (1970) mapping units, in combination with geological data, can serve as the basis of further extrapolation and automated mapping beyond the study area.

2) Development of a quantitative soil-landscape model based on new soil data obtained in the field (qSLM 2).

- **Field data were used as the basis of quantitatively modelling soil resources.** Soil Taxonomic Unit (STU) data obtained in the field in the course of investigating the purity of Wilson's (1970) mapping units (n=145) were used to develop a second, independent soil-landscape model. The lithological data of Gage (1957) and digital terrain attribute data provided predictor variables in the construction of qSLM 1.

- **Methodology.** Sample points were grouped according to parent material classes: 1) primary loess, 2) colluvial/slopewashed loess and 3) geological parent materials. At the location of each observation terrain attributes were determined by intersecting the grid cell corresponding to that location with terrain attribute grids derived from a 25 m DEM. Analysis of variance and DFA were applied to parent material classes. Both stepwise and simultaneous DFA were performed.

- **Results.** There were significant differences in mean terrain attribute values between parent materials (slope and stream power index $P < 0.001$). For stepwise DFA stream power index was the most useful terrain attribute for discrimination between parent materials, although this terrain attribute could not discriminate between colluvial/slopewashed loess and lithological parent materials. Stepwise discrimination was therefore poor. For simultaneous DFA all terrain attributes where $P < 0.05$ (stream power index, slope, plan curvature, log upslope area and profile curvature) were used resulting in fair discrimination, and DFA-derived classification functions ranged 43-66%. Simultaneous DFA functions were used for subsequent mapping.

- **Mapping.** The mapping procedure consisted of allocating 25 m grid cells to STUs on the basis of discriminant function scores calculated from relevant terrain attributes for each grid cell. In areas predicted as having an absence of primary and colluvial/slopewashed loess, grid cells were assigned to soil series on the basis of the underlying geology as determined from the grid coverage of Gage's (1957) geological map. Comparison with Wilson's (1970) map was not considered valid because the two mapping approaches operate at much different resolution of landform and therefore direct comparisons are not meaningful. There were no independent field data for validation. The soil map derived from qSLM 2 is therefore untested.

- **Conclusions.** Geo-referenced sample point locations are essential for the repeatability of pedological observations and correlation with digital terrain attributes and spatial analysis. The nature of DEM-based soil-landscape models means that they can realistically model both the discrete nature of lithological parent materials and the more semicontinuous nature of loess distribution. DFA was successful in discriminating between parent materials on the basis of digital terrain attributes in a realistic manner. However, the DEM may not be of sufficient resolution to accurately predict the occurrence/absence of loess, which may be affected by processes happening over distances smaller than that of the 25 m DEM resolution. More pedological and geological data are required to test and refine qSLM 2, and therefore using qSLM 2 as the basis of extrapolation is not recommended before such validation.

3) Investigation of the relationships between A Horizon percent carbon/nitrogen and soil taxa, parent materials, digital terrain attributes and microclimate data.

- **Carbon (C) and nitrogen (N) are essential components of terrestrial ecosystems.** The amount and spatial variability of C and N is important for understanding landscape and ecological processes, and influences soil fertility and quality. A horizons were sampled in the field to ascertain relationships between these soil properties and soil taxa, parent materials, digital terrain attributes and microclimate data (lowest summer rainfall).

- **Methodology.** At field locations used to investigate the purity of Wilson's (1970) map A horizons were sampled (N=175) and analysed for percent C and N. Nitrogen values were linearly regressed against C values, and analysis of variance compared mean C and N values between soil taxa within parent material types and between parent material types. Carbon and N values were linearly regressed against individual digital terrain attributes derived from a 25 m DEM, and regressed against lowest summer rainfall values from a 30 m microclimate grid.

- **Results.** A horizon percent organic C was a strong predictor of A horizon percent organic N (R^2=0.94). There were no significant differences in mean C, N and C:N values between soil taxa within parent materials, and differences were small but significant (P < 0.001) between parent materials, with calcareous materials having higher values than soils on quartzofeldspathic loess and sediments. Classification of samples according to parent material type explained 24% of the variance in C values and 29% of the variance in N values. Linear regression showed that digital terrain attributes explained no more than 6% and 5% of C and N variance, respectively. Lowest summer rainfall (mm) explained only 4% and 5% of C and N variance, respectively.

- **Conclusions.** Parent materials appear to influence A horizon percent organic C and N, and other research suggests this is due to inherent nutrient properties. However, only only 24% variance in C values and 29% variance in N values can be explained by parent materials. The remaining variance may be due to terrain influences and land management effects not considered here. Carbon and N values are strongly correlated, which supports a wide body of knowledge concerning C:N ratios in soil organic matter. Correlations between C and N values and digital terrain attributes and microclimate data are poor. This can be attributed to the fact that the sampling strategy used here was not designed to test these relationships. In addition, the 25 m DEM from which terrain attributes were derived is of insufficient resolution to represent the scales at which processes affecting C and N are occurring. For more realistic modelling of the spatial distribution of C and N, collection of catena- and catchment-scale data is necessary. Higher-resolution DEMs are required, with a grid cell size of 10 m or less probably necessary to successfully model both terrain characteristics and soil properties (Gessler, 1996).

- **Directions for future research.** For the development of high-resolution soil-landscape models describing the spatial variability of C and N, high-resolution DEMs need to be constructed and detailed terrain analysis done. This needs to be complemented by the collection of soil physical and chemical properties for spatial modelling at a range of scales. For more comprehensive models, detailed geological and microclimate data are necessary. Finally, the impacts on land management need to be incorporated in models of C and N variability.

7.3 The Significance of Quantitative Soil-Landscape Models

The development of quantitative SLMs is one focus of modern pedological research. The criticisms leveled at traditional soil survey – reliance on tacit, subjective knowledge of individual pedologists, qualitative models, lack of spatial databases for observations and generally no statistical data models and treatment of uncertainties – can now be addressed with GPS, GIS and DEMs. Thus the significance of the quantitative models produced in the present work (qSLM 1 and qSLM 2) lies in the fact that they are the first models that quantitatively define the spatial distribution of soil resources in North Otago. While qSLM 1 is still reliant on Wilson's (1970) original data for spatial modeling and therefore incorporates many existing uncertainties and errors concerning spatial locations of samples, qSLM 2 is based on independent field sample sites, the locations of which can be revisited and observations repeated. Another significant advantage is the ease with which sampling schemes can be created in the GIS environment to test the models and validity of resulting soil maps. Although uncertainties are not explicitly presented in the models and maps developed here, future work can ascribe uncertainty values to individual map grid cells.

The models produced here can be used immediately to delineate those soils most suitable for different land uses. While this is admittedly possible using Wilson's (1970) hardcopy soil maps, this process is slow and cumbersome compared to data manipulation in the GIS environment and is unable to utilise specific queries on slope, aspect and other terrain attributes quantitatively and semicontinuously defined by DEMs. One possible application of qSLM 2 and terrain data to land evaluation is presented in Figure 7.1a. A simple GIS query has delineated those calcareous soils (Waikakahi, Oamaru, Roseberry and Tokarahi) that lie on slopes with northerly aspects. These sites show clear potential for viticultural production, although any land use management decision-making must be based on much higher-resolution data gained from site inspection and intensive soil survey, along with other pertinent microclimatic information (Figure 7.1b). These digital soil maps can only serve as a *guide* to resource utilisation, and cannot replace the role of pedologists in providing detailed data and advice to land managers.

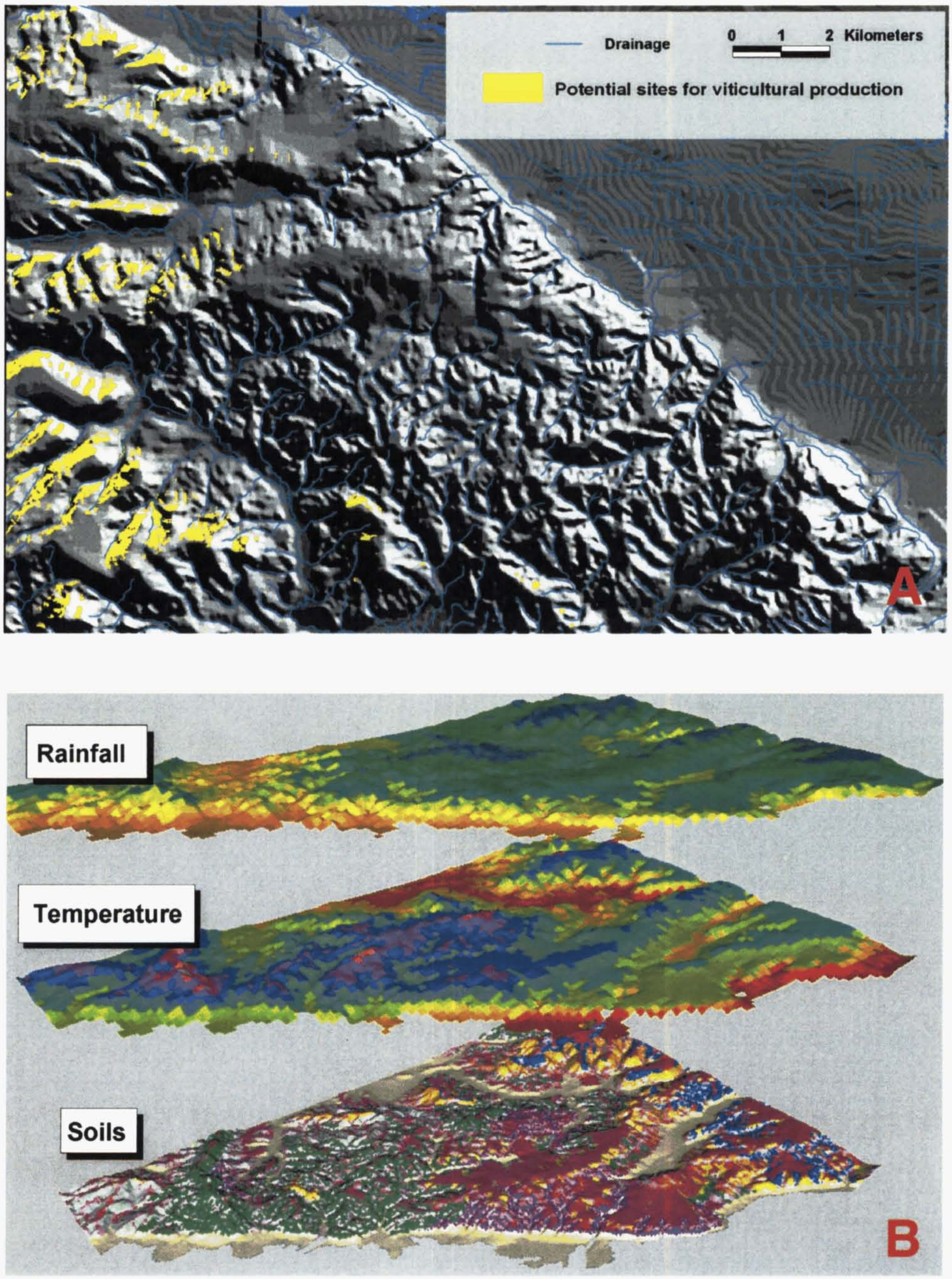


Figure 7.1

Potential applications of qSLM 2.

A) Potential sites for viticultural production can be identified, comprised of areas of calcareous soils with northwest-northeast aspects.

B) Soil data can be combined with rainfall and temperature data (shown here from NIWA, 2001) to investigate relationships between microclimate and soil properties.

A key feature of qSLM 1, and qSLM 2subsequent to validation, is that they can be extended beyond the present study area to the whole of the North Otago downlands, and as such show potential for incorporation into the wider GrowOtago project. This quantitative SLM essentially describes the spatial distribution of loess blanketing the underlying geology and therefore, using Gage's (1957) existing geological data for the downlands, the rules describing loess distribution in the study area can be applied to the wider area. Of course, this approach will only be valid for land systems within similar loess deposition regimes, and therefore more general rules about loess distribution need to be defined before the qSLM 2 methodology can be used. The work of Schmidt *et al.* (2003) is a first step in delineating the locations and extent of South Island loess-mantled landscapes. From such coarse-scale maps of loess landscapes areas of applicability of both qSLM 1 and qSLM 2 can be identified. However, with the known loess deposits in North Otago the opportunity now exists to extend qSLM 1 and qSLM 2 beyond the area in which they were developed to construct more realistic maps of the soil resources of the North Otago downlands.

From the wider perspective of Earth Systems science, qSLM 2 and its possible extensions can be incorporated into models of land systems. With the availability of digital microclimate data and incorporation of quantitatively defined soil-landscapes, the potential exists to quantitatively delineate land systems. Such land system models can serve as the basis for designing further research to investigate whether or not these soil/climate zones influence ecological processes and biodiversity (particularly soil biodiversity).

While no map depicting the spatial variation in C and N was developed in the present work, the development of such models should be a priority for future research. Relationships between parent materials and C and N values were evident from the analysis, and these could serve as the basis of further SLM development. However, more detailed models are required that incorporate terrain attribute predictor variables. Spatial models of important soil physical and chemical properties are essential for informed resource utilisation and management, and also contribute to a wider understanding of fundamental biogeochemical processes and ecological systems. The development of quantitative SLMs will continue to be of relevance to land management and scientific understanding of Earth Surface Systems.

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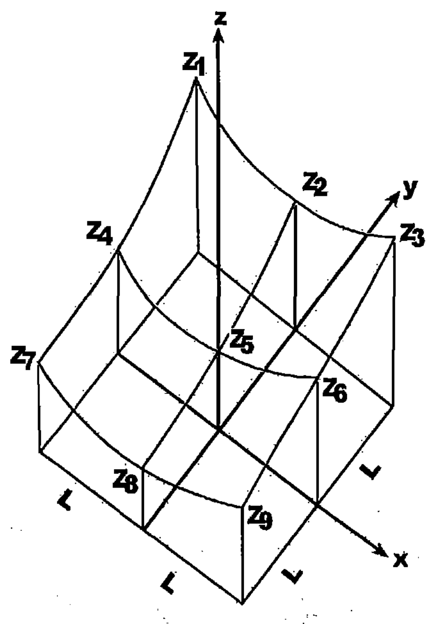
Appendices

Appendix 1 Derivation of Primary Terrain Attributes



Zevenbergen and Thorne (1987) presented a set of equations describing a surface fitted to digital elevation points within a given area (DEM) and associated primary terrain attributes. The equations are based on a 3 × 3 submatrix (left) analysed repetitively throughout the elevation matrix, and all topographic indices are related to the central point of the submatrix. The surface is described by a nine term quadratic equation fitted to the nine points of the 3 × 3 submatrix:

$$\mathrm{Z} = \mathrm{A}x^2y^2 + \mathrm{B}x^2y + \mathrm{C}xy^2 + \mathrm{D}x^2 + \mathrm{E}y^2 + \mathrm{F}xy + \mathrm{G}x + \mathrm{H}y + \mathrm{I}$$

Where the nine parameters are given by

$$A = [(Z_1 + Z_3 + Z_7 + Z_9)/4 - (Z_2 + Z_4 + Z_6 + Z_8)/2 + Z_5]/L^4$$

$$B = [(Z_1 + Z_3 - Z_7 - Z_9)/4 - (Z_2 - Z_8)/2]/L^3$$

$$C = [(-Z_1 + Z_3 - Z_7 + Z_9)/4 + (Z_4 - Z_6)/2]/L^3$$

$$D = [(Z_4 + Z_6)/2 - Z_5]/L^2$$

$$E = [(Z_2 + Z_8)/2 - Z_5]/L^4$$

$$F = (-Z_1 + Z_3 + Z_7 - Z_9)/4L^2$$

$$G = (- Z_4 + Z_6)/2L$$

$$H = (Z_2 - Z_8)/2L$$

$$I = Z_5$$

Terrain attributes derived from the resulting digital elevation surface are found by differentiating equation (1) and solving the resulting equation for the central point of the 3 × 3 submatrix (Zevenbergen and Thorne, 1987). The equations describing slope, aspect, profile curvature and plan curvature are:

$$\beta = slope = \arctan\left(\sqrt{G^2 + H^2}\right)$$

$$\psi = aspect = 180 - \arctan\left(\frac{H}{G}\right) + 90\frac{G}{|G|}$$

(y - axis points north)

$$\phi = \text{profile curvature} = -2\frac{DG^2 + EH^2 + FGH}{G^2 + H^2}$$

$$\omega = \text{plan curvature} = 2\frac{DH^2 + EG^2 - FGH}{G^2 + H^2}$$

Appendix 2 Soil Series in the Study Area

Soils on primary loess parent materials occurring in all physiographic regions (except Downlands Margin Fans and Valley-Fill Alluvium)

Ngapara Series – Typic Laminar Pallic Soil

Ah	0-15 cm	Sandy loam; 10YR 3/2 (very dark greyish brown); slightly firm soil strength, weak fine granular structure; abrupt wavy boundary
AB	15-30 cm	Sandy loam; 10YR 3/2 (very dark greyish brown); slightly firm soil strength, weak medium granular structure; gradual smooth boundary
Bw1	30-50 cm	Sandy loam; 2.5Y 5/3 (greyish brown to light olive brown); very firm soil strength weak medium granular structure; gradual smooth boundary.
Bw2	50-75 cm	Loamy fine sand; 2.5Y 6/3 (light brownish grey to light yellowish brown; slightly firm soil strength, massive; clear smooth boundary.
Bw3	75 cm -	Loamy fine sand; 2.5Y 5/4 (light olive brown); moderately firm soil strength, massive.

Timaru Series – Mottled Fragic Pallic Soil

Ah	0-24 cm	Silt loam; 10YR 2/2 (very dark brown); weak soil strength, moderate fine crumb structure; clear smooth boundary.
AB	24-34 cm	Silt loam; 10YR 4/1 (dark grey) and 2.5Y 5/3 (greyish brown to light olive brown); weak soil strength, weak medium blocky structure; clear wavy boundary.
Bw	34-57 cm	Silt loam; 2.5Y 6/4 (light yellowish brown); weak soil strength, weak coarse blocky structure; clear smooth boundary.
BC(g)	57-67 cm	Silt; 2.5Y 6/2 (light brownish grey) and 7.5YR 4/4 (brown) common coarse distinct secondary mottles; weak soil strength, moderate medium blocky structure; clear wavy boundary.
BC	67-117 cm	Silt; 10YR 5/3 (brown) and 7.5YR 4/4 (light grey) few coarse distinct secondary mottles; strong soil strength, moderate medium blocky structure.

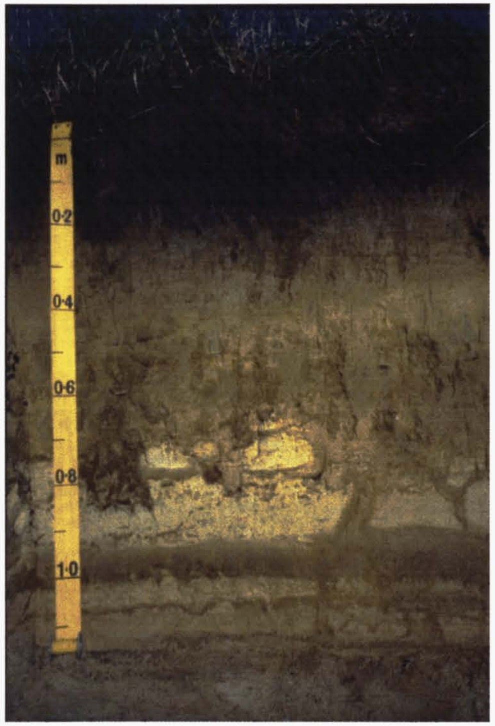
Soils on colluvial/slope-washed loess parent materials occurring in all physiographic regions (except Downlands Margin Fans and Valley-Fill Alluvium)

Brookstead Series – Pallic Soil

Ah	0-30 cm	Sandy loam; 2.5Y 3/1 (brownish black); slightly firm soil strength, moderate fine granular structure; gradual smooth boundary.
AB	30-35 cm	Sandy loam; 2.5Y 4/3 (dark greyish brown to olive brown); strong soil strength, weak medium blocky structure; gradual smooth boundary.
Bw	25-50 cm	Sandy loam; 2.5Y 5/3 (greyish brown to light olive brown); very firm soil strength, massive; clear smooth boundary.
Bw(x)	50-95 cm	Sandy loam; 2.5Y 5/4 (light olive brown); strong soil strength, massive; clear smooth boundary.
BC	95 cm -	Sandy loam; 2.5Y 5/4 (light olive brown); strong soil strength, massive.

Soils on the Downlands Margin Fans

Georgetown Series – Pallic Soil



Ah1	0-11 cm	Silt loam; 10YR 3/2 (very dark greyish brown); weak soil strength, weak fine crumb structure; abrupt wavy boundary.
Ah2	11-25 cm	Silt loam; 10YR 2/2 (very dark brown); weak soil strength, weak fine nutty structure; clear wavy boundary.
AB	25-33 cm	Silt loam; 2.5Y 3/2 (very dark greyish brown) and 2.5Y 5/3 (greyish brown to light olive brown); weak soil strength, weak medium blocky structure; gradual wavy boundary.
Bw	33-60 cm	Silt loam; 2.5Y 6/4 (light yellowish brown); weak soil strength, weak medium blocky structure; clear smooth boundary.
Bx(f)	60-80 cm	Silt loam ; 2.5Y 5/4 (light olive brown) and 10YR 5/6 (yellowish brown) common coarse distinct secondary mottles; strong soil strength, moderate coarse prismatic structure; clear irregular boundary.
BC	80 cm -	Loamy fine sand; 2.5Y 5/6 (yellowish brown); loose soil strength, massive.

Soils on Valley-Fill Alluvium

Awamoko Series – Recent Soil

Ah1	0-5 cm	Gravelly silt loam ; 2.5Y 4/3 (dark greyish brown to olive brown); weak soil strength, weak medium granular structure; clear smooth boundary.
Bw1	5-30 cm	Silt loam; 2.5Y 4/4 (olive brown); moderately firm soil strength, weak fine granular structure; clear irregular boundary.
Bw2	30-60 cm	Silt loam; 2.5Y 5/4 (yellowish brown); moderately firm soil strength, weak fine granular structure; clear smooth boundary.
bA	60-75 cm	Silt loam; 2.5Y 4/2 (Dark greyish yellow); moderately firm soil strength, weak fine granular structure; clear abrupt boundary.
b2C	75 cm -	Quartz gravels

Soils on Gravels of the High Terraces

Taiko Series – Pallic Soil

Ah	0-30 cm	Gravelly silt loam; 2.5Y 3/2 (very dark greyish brown) ; weak soil strength, moderate medium crumb structure.; gradual smooth boundary.
AB	30-40 cm	Gravelly silt loam; 2.5Y 3/3 (dark olive brown); weak soil strength, moderate medium crumb structure; gradual smooth boundary.
Bw	40-65 cm	Gravelly, stony silt loam; 2.5Y 4/3 (dark greyish brown to olive brown); strong soil strength, weak medium blocky structure; gradual irregular boundary.
C	65 cm -	Greywacke gravels plugged with silts and clays.

Soils on Mesas and Buttes of the Limestone Tablelands

Waikakahi Series – Vertic Melanic Soil

Ah	0-35 cm	Silt loam; 2.5Y 3/2 (very dark greyish brown); moderately firm soil strength, moderate medium granular structure; gradual smooth boundary.
Bw	35-75 cm	Silt loam; 10YR 6/6 (brownish yellow); strong soil strength, strong medium blocky structure; gradual smooth boundary.
Bwk	75-140 cm	Silt loam; 10YR 7/6 (yellow); strong soil strength, moderate coarse blocky structure; gradual smooth boundary.
BCk	140 cm -	Weathered limestone

Oamaru Series – Rendzic Melanic Soil

Ah	0-20 cm	Silt loam; 10YR 3/2 (very dark greyish brown); weak soil strength, strong medium granular structure; clear irregular boundary.
R	20 cm -	Limestone bedrock.

Soils on Mesas and Buttes of the Limestone Tablelands

Roseberry Series – Melanic Soil

Ah	0-20 cm	Silt loam; 10YR 3/2 (very dark greyish brown); weak soil strength, moderate medium granular structure; gradual smooth boundary.
AB	20-30 cm	Clay loam; 2.5Y 3/2 (very dark greyish brown); slightly firm soil strength, strong medium nutty structure; gradual irregular boundary.
Bw	30-55 cm	Clay loam; 2.5Y 6/4 (light yellowish brown); moderately firm strength, moderate medium nutty structure; clear wavy boundary.
BCk	55 cm -	Clay loam; 2.5Y 6/4 (light yellowish brown); moderately firm strength, massive.

Tokarahi Series – Melanic Soil

Ah	0-20 cm	Silt loam; 2.5Y 3/2 (very dark greyish brown); moderately firm soil strength, strong medium granular structure; gradual smooth boundary.
AB	20-30 cm	Silty clay loam; 2.5Y 3/3 (dark olive brown); moderately firm soil strength, moderate medium granular structure; gradual irregular boundary.
Bw	30-70 cm	Clay loam; 2.5Y 4/4 (olive brown); very firm soil strength, moderate coarse blocky structure; clear irregular boundary.
C		Weathered calcareous glauconitic sandstone.

Soils on Loess-Mantled Dissected Hill Country

Airedale Series – Pallic Soil

Ah	0-5 cm	Silt loam; 10YR 4/3 (brown); weak soil strength, moderate fine granular structure; clear smooth boundary.
Bw	5-30 cm	Silt loam; 10YR 5/3 (brown) and 10YR 6/6 (brownish yellow) few medium distinct secondary mottles; strong soil strength, weak medium blocky structure; diffuse irregular boundary.
BC	30-40 cm	Silt loam; 10YR 5/3 (brown) and 10YR 5/6 (yellowish brown) many coarse distinct secondary mottles; strong soil strength, weak coarse blocky structure; diffuse irregular boundary.
C	40 cm -	Siltstone.

Kauru Series – Pallic Soil

Ah	0-10 cm	Silt loam; 10YR 3/1 (very dark grey); slightly firm soil strength, moderate coarse granular structure; clear wavy boundary.
AB	10-25 cm	Silt loam; 10YR 2/2 (very dark brown); very firm soil strength, weak fine blocky structure; gradual smooth boundary.
Bw	25-50 cm	Silt loam; 10YR 6/4 (light yellowish brown) and 7.5YR 6/8 (reddish yellow) many medium distinct secondary mottles; strong soil strength, weak coarse blocky structure; gradual irregular boundary.
C	50 cm -	Sandstone

Soils on Loess-Mantled Dissected Hill Country

Papakaio Series – Pallic Soil

Ah	0-20 cm	Silt loam; 10YR 3/2 (very dark greyish brown); slightly firm soil strength, weak fine granular structure; clear smooth boundary.
AB	20-35 cm	Silt loam; 10YR 4/2 (dark greyish brown); slightly firm soil strength, weak medium granular structure; clear smooth boundary.
Bw	35-45 cm	Silt loam; 10YR 6/4 (light yellowish brown); slightly firm soil strength, weak medium granular structure; clear smooth boundary.
C	45 cm -	Quartz gravels.

Soils on Steep Gullies in Schist

Bortons Series

Ah	0-15 cm	Silt loam; 2.5Y 3/3 (dark olive brown); weak soil strength, moderate medium granular structure; gradual smooth boundary.
BC	15-40 cm	Stony silt loam; 2.5Y 5/4 (yellowish brown); weak soil strength, moderate medium granular structure; abrupt irregular boundary.
R	40 cm-	Semischist.

Appendix 3 Soil Descriptions

Texture

cl	clay loam	**sl**	sandy loam
gcl	gravelly clay loam	**gfsl**	gravelly fine sandy loam
gzcl	gravelly silty clay loam	**gsl**	gravelly sandy loam
zl	silt loam	**gls**	gravelly loamy sand
czl	coarse silt loam	**s**	sand
gzl	gravelly silt loam	**fs**	fine sand
fsl	fine sandy loam	**fg**	fine gravel

Soil

Ai	Airedale	**Om**	Oamaru
Ar	Ardgowan	**Pk**	Papakaio
Aw/Ef	Awamoko/Enfield	**Rb**	Roseberry
Bo	Bortons	**Tk**	Taiko
Br	Brookstead	**Tt**	Taitapu
Ge	Georgetown	**Ti**	Timaru
Ku	Kauru	**To**	Tokarahi
Ng	Ngapara	**Wk**	Waikakahi

Sample	Easting	Northing	Elev. (m)	Horizon	(cm)	Colour(s), moist	Texture	% C	% N	Soil
1	2345253.8	5576034.2	238.9	A	0-20	2.5Y 3/2	zl	3.2	0.3	Ai
				AB	20-25	2.5Y 3/2, 2.5Y 5/3	zl			
				Bw	25-75	2.5Y 5/3	zl			
				C	75-					
2	2349460.6	5577579.0	116.6	A	0-15	2.5Y 3/1	zl	4.2	0.4	Ai
				AB	15-25	2.5Y 3/1, 2.5Y 7/4	zl			
				Bwt	25-45	2.5Y 5/4	zcl			
				C	45-					
3	2349481.2	5577643.3	111.8	A	0-20	2.5Y 4/1	zl	5.1	0.5	Ai
				AB	20-25	2.5Y 3/2, 2.5Y 6/4	zl			
				Bwt	25-60	2.5Y 5/4	zl			
				Bw	60-	2.5Y 6/4	czl			
4	2348187.5	5577714.8	131.6	A	0-20	2.5Y 3/2	zl	2.3	0.2	Ai
				AB	20-25	2.5Y 3/2, 2.5Y 5/3	zl			
				Bw	25-50	2.5Y 5/3	zl			
				C	50-					
5	2347532.0	5577420.5	140.2	A	0-20	2.5Y 3/2	zl	4.6	0.4	Ai
				AB	20-25	2.5Y 3/2, 2.5Y 5/3	zl			
				Bw	25-60	2.5Y 5/3	zl			
				C	60-					
6	2348293.7	5577815.4	137.7	A	0-20	2.5Y 3/2	zl	3.7	0.3	Ai
				AB	20-25	2.5Y 3/2, 2.5Y 5/3	zl			
				Bw	25-40	2.5Y 5/3	zl			
				C	40-					
7	2345095.1	5576012.2	231.1	A	0-20	2.5Y 3/2	zl	3.4	0.3	Ai
				AB	20-30	2.5Y 3/2, 2.5Y 5/3	zl			
				Bw	30-60	2.5Y 5/3	zl			
				C	60-					
8	2348890.6	5577900.9	122.5	A	0-20	2.5Y 4/1	zl	3.3	0.3	Ar
				AB	20-25	2.5Y 3/2, 2.5Y 6/4	zl			
				Bwt	25-60	2.5Y 5/4	zl			
				Bw	60-	2.5Y 6/4	czl			
9	2345216.0	5579731.8	170.7	A	0-30	2.5Y 3/2	zl	3.3	0.3	Ar
				AB	30-40	2.5Y 3/3	zl			
				Bw(t)	40-80	2.5Y 5/4	zl			
				Bt	80-120	2.5Y 6/4	czl			
				BC	120-	2.5Y 6/4	czl			
10	2344745.8	5579308.9	152.0	A	0-20	2.5Y 3/2	zl	3.5	0.3	Ar
				AB	20-25	2.5Y 3/3	zl			
				Bw(t)	25-50	2.5Y 5/4	zl			
				BC	50-115	2.5Y 6/4	czl			
				C	115-					
11	2341873.2	5578063.7	188.1	A	0-13	2.5Y 3/3	zl	3.4	0.3	Ar
				AB	13-30	2.5Y 5/3	zl			
				Bw(t)1	30-50	2.5Y 6/3	zl			
				Bt1	50-90	2.5Y 6/3	czl			
				Bw(t)2	90-110	2.5Y 6/3	czl			
				Bt2	110-140	2.5Y 6/3	czl			
				BC	140-					

Sample	Easting	Northing	Elev. (m)	Horizon	(cm)	Colour(s), moist	Texture	% C	% N	Soil
12	2348957.0	5577634.1	91.9	A	0-13	2.5Y 3/2	zl	5.0	0.4	Ar
				AB	13-20	2.5Y 6/6, 2.5Y 3/3	zl			
				Bw(t)	20-50	2.5Y 5/4	zl			
				Bw	50-100	2.5Y 6/4	zl			
				C	100-					
13	2347253.9	5577542.1	182.7	A	0-20	2.5Y 3/2	zl	3.0	0.3	Ar
				AB	20-30	2.5Y 3/2, 2.5Y 5/4	zl			
				Bw(t)	30-60	2.5Y 5/4	czl			
				Bw	60-90	2.5Y 5/4	czl			
				C	90-					
14	2347382.8	5575752.1	133.9	A	0-30	2.5Y 3/2	zl	3.0	0.3	Aw/Ef
				AB	30-40	2.5Y 3/2, 2.5Y 7/2	zl			
				Bg	40-80	2.5Y 7/2	czl			
				Bgr	80-	2.5Y 7/2, 10YR 3/8	czl			
15	2331615.5	5584516.3	174.7	A	0-20	10YR 4/2	fsl	2.9	0.3	Aw/Ef
				AB	20-30	10YR 4/2, 10YR 6/4	fsl			
				Bw(t)	30-90	10YR 6/4	fsl			
				Bw	90-120	10YR 6/6	fsl			
16	2330703.0	5584722.3	175.8	A	0-15	2.5Y 4/3	zl	3.3	0.3	Aw/Ef
				AB	15-20	2.5Y 4/3	czl			
				Bw	20-120	2.5Y 5/4	fsl			
				bA	120-125	2.5Y 4/2	zl			
				bBw	125-	2.5Y 5/4	czl			
17	2333516.2	5584930.3	164.4	A	0-20	10YR 3/3	fsl	2.6	0.3	Aw/Ef
				AB	20-25	10YR 3/3, 10YR 5/6	fsl			
				Bw1	25-55	10YR 5/6	ls			
				Bw2	55-125	2.5Y 5/6	fs			
18	2332513.4	5585634.0	183.5	A	0-30	2.5Y 3/2	zl	4.0	0.4	Aw/Ef
				AB	30-65	2.5Y 3/3	zl			
				R	65-					
19	2332616.9	5584496.6	167.8	A	0-25	2.5Y 4/2	ls	2.9	0.3	Aw/Ef
				AB	25-30	2.5Y 4/2, 2.5Y 4/6	fsl			
				Bw(g)	30-110	2.5Y 4/6, 2.5Y 7/3	fsl			
20	2331703.5	5584575.5	171.2	A	0-20	10YR 4/2	zl	3.1	0.3	Aw/Ef
				AB	20-30	10YR 4/2, 10YR 5/6	zl			
				Bw(t)	30-60	10YR 5/8	fsl			
21	2337312.7	5586093.4	153.6	A	0-25	2.5Y 3/2	czl	3.5	0.3	Bo
				R	25-					
22	2336609.6	5588525.1	130.7	A	0-5	2.5Y 4/4	gzl	7.9	0.8	Bo
				R	5-					
23	2338448.8	5585239.7	165.8	A	0-12	2.5Y 3/3	czl	8.2	0.7	Bo
				R	12-					
24	2337592.6	5587830.2	114.0	A	0-15	2.5Y 4/4	gzl	2.4	0.3	Bo
				R	15-					
25	2336748.2	5588439.4	113.7	A	0-17	2.5Y 4/4	gzl	3.8	0.4	Bo
				R	17-					

Sample	Easting	Northing	Elev. (m)	Horizon	(cm)	Colour(s), moist	Texture	% C	% N	Soil
26	2337197.2	5586084.9	148.5	A	0-25	2.5Y 3/3	czl	2.6	0.2	Bo
				Bw	25-35	2.5Y 4/3	czl			
				R	35-					
27	2338066.9	5586431.7	155.4	A	0-15	2.5Y 3/3	czl	3.8	0.3	Bo
				R	15-					
28	2340741.9	5585120.9	129.2	A	0-10	2.5Y 3/3	czl	1.7	0.2	Bo
				Bw	10.-35	2.5Y 5/3	czl			
				C	35-					
29	2341348.1	5582264.0	194.0	A	0-13	2.5Y 3/2	czl	4.1	0.4	Bo
				R	13-					
30	2337566.8	5587433.1	160.9	A	0-15	2.5Y 3/1	zl	6.5	0.6	Bo
				AC	15-20	2.5Y 3/1	gzl			
				C	20-					
31	2332306.7	5585718.5	200.1	A	0-20	2.5Y 3/2	czl	4.3	0.4	Br
				AB	20-25	2.5Y 3/3	czl			
				Bw	25-95	2.5Y 5/3	fsl			
				Bwt	95-120	2.5Y 6/4	ls			
				Bw2	120-	2.5Y 6/4	ls			
32	2341500.9	5581580.1	171.2	A	0-15	2.5Y 3/2	czl	4.5	0.3	Br
				AB	15-20	2.5Y 3/3	czl			
				Bw(t)	20-50	2.5Y 6/4	czl			
				Bw	50-	2.5Y 6/4	ls			
33	2332037.2	5587430.1	227.5	A	0-20	2.5Y 3/2	zl	2.6	0.3	Br
				AB	20-25	2.5Y 3/3	zl			
				Bw(t)	25-	2.5Y 5/4	zl			
34	2341280.0	5584425.0	114.3	A	0-30	2.5Y 3/2	czl	3.1	0.3	Br
				AB	30-40	2.5Y 3/2, 2.5Y 5/4	czl			
				Bw	40-80	2.5Y 5/4	czl			
				Bwt	80-	2.5Y 5/4	czl			
35	2341813.5	5583974.0	113.3	A	0-15	2.5Y 3/2	czl	2.5	0.2	Br
				AB	15-25	2.5Y 3/2	czl			
				Bw	25-55	2.5Y 5/4	czl			
				Bwt	55-70	2.5Y 5/4	czl			
				Bt	70-	2.5Y 6/4	czl			
36	2332591.0	5583451.9	248.4	A	0-25	2.5Y 3/2	gzl	4.3	0.4	Br
				AB	25-30	2.5Y 3/3	gzl			
				Bwt	30-80	2.5Y 4/4	gzl			
				Bwt	80-115	2.5Y 7/4/6	ls			
				BC	115-					
37	2336267.7	5582790.4	179.6	A	0-30	2.5Y 3/3	czl	2.5	0.2	Br
				AB	30-35	2.5Y 4/4	czl			
				Bw(t)	35-100	2.5Y 5/6	czl			
				BC	100-135	2.5Y 5/6	fsl			
				C	135-					
38	2334527.2	5582638.3	160.5	A	0-45	2.5Y 3/3	czl	4.2	0.4	Br
				AB	45-65	2.5Y 4/4	czl			
				Bwt	65-125	2.5Y 5/6	czl			
				BC	125-	2.5Y 5/6	fsl			

Sample	Easting	Northing	Elev. (m)	Horizon	(cm)	Colour(s), moist	Texture	% C	% N	Soil
39	2337104.6	5581814.0	220.7	A	0-10	2.5Y 3/3	czl	2.5	0.2	Br
				AB	10.-15	2.5Y 4/4	czl			
				Bt	15-40	2.5Y 6/4	czl			
				Bw	40-100	2.5Y 6/4	fsl			
				Bw(t)	100-	2.5Y 6/4	fsl			
40	2338380.3	5580033.1	235.9	A	0-20	2.5Y 3/2	zl	4.4	0.4	Br
				AB	20-25	2.5Y 3/3	zl			
				Bg	25-50	2.5Y 6/8, 2.5Y 8/4	czl			
				Bw(t)	50-140	2.5Y 5/4	czl			
				Bw(x)	140-	2.5Y 6/4	ls			
41	2331795.7	5582107.9	160.7	A	0-10	2.5Y 3/3	czl	2.4	0.2	Br
				AB	10.-15	2.5Y 4/3	czl			
				Bw	15-140	2.5Y 5/4	fsl			
				C	140-					
42	2336397.6	5582113.5	183.0	A	0-30	2.5Y 3/3	czl	2.8	0.3	Br
				AB	30-40	2.5Y 4/3	czl			
				Bt	40-120	2.5Y 5/4	czl			
				Bw	120-190	2.5Y 6/4	ls			
				C	190-					
43	2333071.7	5583886.4	197.7	A	0-25	2.5Y 3/3	czl	3.2	0.3	Br
				AB	25-35	2.5Y 4/3	czl			
				Bwt	35-120	2.5Y 5/3	czl			
				Bw	120-	2.5Y 6/4	ls			
44	2329965.9	5582714.2	235.3	A	0-20	2.5Y 4/2	zl	3.8	0.4	Br
				AB	20-25	2.5Y 4/2	czl			
				Bw	25-	2.5Y 6/4	czl			
45	2338910.9	5587002.7	104.4	A	0-20	2.5Y 3/3	zl	2.3	0.2	Ge
				AB	20-25	2.5Y 3/3, 2.5Y 5/3	zl			
				Bg	25-95	2.5Y 5/3, 10YR 6/8	czl			
				C	95-					
46	2339666.9	5587301.0	90.9	A	0-18	2.5Y 3/3	zl	2.5	0.3	Ge
				AB	18-23	2.5Y 3/3, 2.5Y 5/3	zl			
				BW	23-	2.5Y 5/3	czl			
47	2342083.4	5583879.0	99.1	A	0-25	2.5Y 3/3	zl	2.7	0.3	Ge
				AB	25-40	2.5Y 3/3, 2.5Y 5/3	zl			
				Bg	40-	2.5Y 5/3, 10YR 6/8	czl			
48	2343525.3	5582699.2	103.2	A	0-30	2.5Y 3/3	czl	5.0	0.4	Ge
				AB	30-45	2.5Y 3/3, 2.5Y 5/4	czl			
				Bt	45-110	2.5Y 5/4	czl			
				Bw(t)	110-	2.5Y 5/4	czl			
49	2342052.2	5583713.1	122.8	A	0-30	2.5Y 3/3	gzl	2.7	0.2	Ge
				AB	30-40	2.5Y 3/3, 2.5Y 5/3	gzl			
				Bw	40-	2.5Y 5/3	gzl			
50	2340493.6	5586782.2	94.7	A	0-20	2.5Y 3/3	zl	2.1	0.2	Ge
				AB	20-25	2.5Y 3/3, 2.5Y 5/3	zl			
				Bw	25-40	2.5Y 5/3	gzl			
				C	40-					

Sample	Easting	Northing	Elev. (m)	Horizon	(cm)	Colour(s), moist	Texture	% C	% N	Soil
51	2340903.7	5585482.2	89.8	A	0-20	2.5Y 3/3	zl	2.0	0.2	Ge
				AB	20-30	2.5Y 3/3, 2.5Y 5/6	zl			
				Bw(g)	30-90	2.5Y 5/6, 10YR 5/8	ls			
				C	90-		fg			
52	2343697.6	5583160.7	85.7	A	0-25	2.5Y 3/3	czl	2.6	0.3	Ge
				AB	25-35	2.5Y 3/3, 2.5Y 5/4	czl			
				Bwg	35-	2.5Y 5/4	ls			
53	2340386.9	5586711.0	90.8	A	0-20	2.5Y 3/3	zl	2.3	0.2	Ge
				AB	20-25	2.5Y 3/3, 2.5Y 5/3	zl			
				Bw	25-60	2.5Y 5/3	gzl			
				C	60-					
54	2340981.3	5585253.4	94.6	A	0-20	2.5Y 3/3	zl	2.3	0.2	Ge
				AB	20-25	2.5Y 3/3, 2.5Y 5/3	zl			
				Bg	25-	2.5Y 5/3, 10YR 6/8	czl			
55	2334723.7	5588214.3	118.1	A	0-20	2.5Y 3/2	zl	2.7	0.3	Ge
				AB	20-27	2.5Y 5/3	zl			
				Bw	27-60	2.5Y 5/4	gzl			
56	2336886.5	5583047.8	196.8	A	0-7	2.5Y 3/3	czl			Ku
				AB	7.-15	2.5Y 4/4	czl			
				Bwt	15-70	2.5Y 5/6	ls			
				BC	70-105	2.5Y 6/6	ls			
				C	105-					
57	2335396.1	5584809.4	194.3	A	0-30	2.5Y 3/3	zl	2.3	0.2	Ku
				AB	30-35	2.5Y 4/3	czl			
				Bwt	35-95	2.5Y 4/4	czl			
				Bw	95-190	2.5Y 6/4	ls			
				BC	190-210	2.5Y 5/6	ls			
				C	210-					
58	2333813.6	5582817.5	224.7	A	0-3	2.5Y 3/3	czl	3.3	0.3	Ku
				Bw	30-60	2.5Y 6/4	czl			
				C	60-					
59	2338653.5	5578114.3	109.8	A	0-15	2.5Y 3/3	czl	2.6	0.2	Ku
				AB	15-25	2.5Y 4/3	czl			
				Bw	25-100	2.5Y 4/4	ls			
				C	100-					
60	2333848.9	5585589.6	168.4	A	0-15	2.5Y 3/3	zl	4.6	0.4	Ng
				AB	15-20	2.5Y 4/3	czl			
				Bw	20-165	2.5Y 6/4	ls			
				C	165-					
61	2334508.2	5585860.0	175.6	A	0-17	2.5Y 3/3	zl	4.3	0.4	Ng
				AB	17-30	2.5Y 3/4	czl			
				Bwt	30-100	2.5Y 6/4	fsl			
				C	100-					
62	2332904.1	5587206.5	221.8	A	0-17	2.5Y 3/2	czl	2.9	0.3	Ng
				AB	17-22	2.5Y 5/3	czl			
				Bw1	22-50	2.5Y 6/3	czl			
				B(t)	50-70	2.5Y 6/4	czl			
				Bw2	70-100	2.5Y 6/4	czl			
				C	100-140	2.5Y 6/4	ls			

Sample	Easting	Northing	Elev. (m)	Horizon	(cm)	Colour(s), moist	Texture	% C	% N	Soil
63	2334120.3	5584565.9	183.8	A	0-25	2.5Y 3/3	fsl	2.3	0.2	Ng
				AB	25-30	2.5Y 4/3	fsl			
				Bw(t)	30-60	2.5Y 5/4	fsl			
				Bw1	60-100	2.5Y 6/4	ls			
				Bw2	100-140	2.5Y 6/4	ls			
				C	140-					
64	2338438.5	5580695.4	274.9	A	0-15	2.5Y 3/3	czl	4.4	0.4	Ng
				AB	15-20	2.5Y 4/4	czl			
				Bw	20-65	2.5Y 6/4	czl			
				Bwt	65-100	2.5Y 6/4	fsl			
				C	100-					
65	2331540.7	5589239.1	162.9	A	0-20	2.5Y 3/3	zl	2.7	0.3	Ng
				AB	20-25	2.5Y 3/3	zl			
				Bw	25-50	2.5Y 6/4	czl			
				Bt(x)	50-70	2.5Y 6/4	czl			
				C	70-	2.5Y 6/4	fs			
66	2330199.1	5586936.5	266.3	A	0-25	2.5Y 3/2	czl	2.5	0.2	Ng
				AB	25-30	2.5Y 3/3	czl			
				Bw(t)	30-90	2.5Y 6/4	fsl			
				Bw2	90-	2.5Y 6/4	fsl			
67	2330141.3	5584166.1	240.9	A	0-20	2.5Y 3/2	zl	4.3	0.4	Ng
				AB	20-25	2.5Y 4/4	czl			
				Bw(t)	25-75	2.5Y 5/4	czl			
				Bw	75-95	2.5Y 6/4	fsl			
				R	95-					
68	2330539.2	5584065.3	241.1	A	0-20	2.5Y 3/3	czl	2.9	0.3	Ng
				AB	20-25	2.5Y 4/3	czl			
				Bw(t)	25-75	2.5Y 5/3	czl			
				Bw	75-120	2.5Y 6/4	fls			
				C	120-					
69	2330619.5	5584012.5	245.7	A	0-15	2.5Y 3/3	czl	2.7	0.3	Ng
				AB	15-20	2.5Y 4/3	czl			
				Bw(t)	20-90	2.5Y 5/3	czl			
				Bw	90-140	2.5Y 6/4	fls			
				C	140-					
70	2341504.9	5581300.6	206.2	A	0-14	2.5Y 3/3	czl	3.1	0.3	Ng
				AB	14-20	2.5Y 4/3	czl			
				Bw(t)	20-65	2.5Y 6/4	czl			
				Bw	65-	2.5Y 6/4	ls			
71	2341227.5	5581143.2	221.2	A	0-20	2.5Y 3/3	czl	4.6	0.4	Ng
				AB	20-25	2.5Y 4/3	czl			
				Bw	25-85	2.5Y 6/4	czl			
				Bw(t)	85-160	2.5Y 6/4	ls			
				C	160-					
72	2330236.3	5588363.9		A	0-25	2.5Y 3/3	zl	3.0	0.3	Ng
				AB	25-30	2.5Y 3/3	zl			
				Bw	30-60	2.5Y 6/4	czl			
				Bt(x)	60-100	2.5Y 6/4	czl			
				C	100-	2.5Y 6/4	fs			

Sample	Easting	Northing	Elev. (m)	Horizon	(cm)	Colour(s), moist	Texture	% C	% N	Soil
73	2330132.9	5584928.3	238.9	A	0-30	2.5Y 3/2	zl	3.2	0.3	Ng
				AB	30-35	2.5Y 3/3	zl			
				Bwt	35-90	2.5Y 5/4	czl			
				R	90-					
74	2330440.4	5584849.1	240.2	A	0-30	2.5Y 3/2	zl	5.8	0.6	Ng
				AB	30-35	2.5Y 3/3	zl			
				R	35-					
75	2331818.5	5584374.5		A	0-27	2.5Y 3/2	zl	6.2	0.6	Ng
				R	27-					
76	2338866.5	5581041.4	235.3	A	0-13	2.5Y 4/2	czl	3.7	0.3	Ng
				AB	13-20	2.5Y 4/4	czl			
				Bw1	20-40	2.5Y 6/4	czl			
				Bw(t)1	40-60	2.5Y 6/4	fsl			
				Bw2	60-140	2.5Y 6/4	czl			
				Bw(t)2	140-	2.5Y 6/4	fsl			
77	2333940.2	5582477.2	185.0	A	0-15	2.5Y 3/2	czl	4.3	0.4	Ng
				AB	15-20	2.5Y 3/3	czl			
				Bwt	20-65	2.5Y 5/4	czl			
				Bw	65-100	2.5Y 6/4	czl			
				C	100-					
78	2330715.5	5586215.4	264.2	A	0-20	2.5Y 3/3	czl	2.4	0.2	Ng
				AB	20-25	2.5Y 4/3	czl			
				Bwt	25-155	2.5Y 6/4	fsl			
79	2334368.8	5583484.3		A	0-24	2.5Y 3/3	czl	3.1	0.3	Ng
				AB	24-30	2.5Y 4/2	czl			
				Bwt	30-110	2.5Y 6/4	czl			
				Bw	110-	2.5Y 6/4	fs			
80	2330124.3	5580920.0	262.5	A	0-15	2.5Y 3/3	czl	2.5	0.2	Ng
				AB	15-20	2.5Y 3/3, 2.5Y 5/4	czl			
				Bw	20-60	2.5Y 5/4	czl			
				Bw(g)	60-	2.5Y 6/4	fsl			
81	2330696.4	5589985.5	188.2	A	0-25	2.5Y 3/3	czl	2.6	0.3	Ng
				AB	25-30	2.5Y 5/3	czl			
				Bw	30-60	2.5Y 6/4	czl			
				Bt(x)	60-100	2.5Y 5/3	czl			
				C	100-	2.5Y 6/4	fsl			
82	2330214.0	5585337.3	266.4	A	0-20	2.5Y 3/2	czl	2.8	0.3	Ng
				AB	20-24	2.5Y 3/3	czl			
				Bw(t)	24-50	2.5Y 5/4	czl			
				Bt(x)	50-80	2.5Y 5/4	fsl			
				Bw(t)2	80-	2.5Y 6/4	fsl			
83	2331891.7	5587077.0	259.5	A	0-20	2.5Y 3/2	czl	3.0	0.3	Ng
				AB	20-25	2.5Y 5/3	czl			
				Bw1	25-60	2.5Y 6/3	czl			
				B(t)	60-80	2.5Y 6/4	czl			
				Bw2	80-100	2.5Y 6/4	czl			
				C	100-	2.5Y 6/4	ls			

Sample	Easting	Northing	Elev. (m)	Horizon	(cm)	Colour(s), moist	Texture	% C	% N	Soil
84	2330486.4	5585673.8	261.6	A	0-25	2.5Y 3/2	czl	2.3	0.2	Ng
				AB	25-30	2.5Y 3/3	czl			
				Bw(g)	30-135	2.5Y 5/3	fsl			
				Bw	135-	2.5Y 5/4	sl			
85	2333903.9	5586196.6	246.2	A	0-17	2.5Y 3/2	zl	3.5	0.3	Ng
				AB	17-24	2.5Y 4/4	czl			
				Bw(t)	24-70	2.5Y 5/4	czl			
				Bw	70-145	2.5Y 6/4	ls			
				C	145-					
86	2331091.5	5583875.4	228.8	A	0-25	2.5Y 3/2	zl	8.1	0.8	Om
				R	25-					
87	2330481.9	5584107.5	228.0	A	0-20	2.5Y 3/2	zl	6.5	0.7	Om
				R	20-					
88	2341762.2	5579443.1	210.8	A	0-20	2.5Y 3/2	gls	4.0	0.3	Pk
				AB	20-25	2.5Y 4/2	gls			
				Bw	25-50	2.5Y 6/4	gls			
				C	50-					
89	2342121.7	5579052.9	186.6	A	0-25	2.5Y 3/2	gls	3.8	0.3	Pk
				C	25-					
90	2337291.8	5581171.9	233.6	A	0-25	2.5Y 3/3	zl	3.3	0.3	Pk
				AB	25-30	2.5Y 5/2	czl			
				Bg	30-100	2.5Y 7/3, 10YR 5/8	czl			
				BgC	100-	2.5Y 7/3, 10YR 5/8	czl			
91	2341001.3	5580954.4	238.3	A	0-25	2.5Y 3/3	czl	3.5	0.3	Pk
				AB	25-30	2.5Y 5/4	gzl			
				Bw(t)	30-65	2.5Y 6/4	gzl			
				C	65-					
92	2345952.7	5580562.7	94.4	A	0-20	2.5Y 3/2	gzl	2.3	0.2	Pk
				C	20-					
93	2342074.8	5579344.4	173.4	A	0-10	2.5Y 3/2	gls	3.5	0.3	Pk
				AB	10.-17	2.5Y 4/2	gls			
				Bw	17-26	2.5Y 6/4	gls			
				C	26-					
94	2343325.1	5577881.0	110.6	A	0-30	2.5Y 3/3	czl	3.4	0.3	Pk
				AB	30-40	2.5Y 4/4	czl			
				Bw	40-65	2.5Y 4/4	czl			
				C	65-					
95	2332776.8	5581981.9	139.7	A	0-25	2.5Y 3/3	gzl	6.2	0.5	Pk
				AB	25-30	2.5Y 4/2	gzl			
				Btg	30-100	2.5Y 5/4, 10YR 5/8	gzl			
				C	100-					
96	2334423.6	5581850.3	144.4	A	0-3	2.5Y 4/4	gzl	2.2	0.2	Pk
				AB	3-10.	2.5Y 4/4	gzl			
				Bw1	10.-70	2.5Y 4/6	gzl			
				Bw2	70-95	2.5Y 5/6	gsl			
				C	95-					

Sample	Easting	Northing	Elev. (m)	Horizon	(cm)	Colour(s), moist	Texture	% C	% N	Soil
97	2342017.5	5580358.9	272.2	A	0-15	2.5Y 3/2	gls	3.4	0.3	Pk
				AB	15-20	2.5Y 4/2	gls			
				Bw	20-65	2.5Y 6/4	gls			
				C	65-					
98	2338043.2	5578639.0	207.5	A	0-20	2.5Y 4/3	zl	4.4	0.3	Rb
				AB	20-25	2.5Y 3/1, 2.5Y 5/4	zl			
				Bwk	25-70	2.5Y 6/4	zl			
				BC	70-	2.5Y 5/4	zl			
99	2331091.3	5584828.9	214.1	A	0-20	2.5Y 3/2	zl	8.6	0.7	Rb
				AC	20-30	2.5Y 3/2	zl			
				C	30-					
100	2330492.1	5584775.3	224.0	A	0-15	2.5Y 3/2	zl	8.6	0.7	Rb
				C	15-					
101	2331556.6	5585164.0	217.6	A	0-20	2.5Y 3/2	czl	2.5	0.2	Rb
				AB	20-25	2.5Y 3/1, 2.5Y 4/4	czl			
				Bw(k)	25-75	2.5Y 5/6, 2.5Y 8/3	czl			
				BCk	75-110	2.5Y 6/6, 5YR 4/4	fsl			
102	2331466.8	5584874.3	201.3	A	0-20	10YR 3/2	zl	5.5	0.6	Rb
				R	20-					
103	2331070.9	5584836.7	219.7	A	0-20	2.5Y 3/2	zl	5.2	0.5	Rb
				AB	20-25	2.5Y 3/3	zl			
				Bw	25-60	2.5Y 4/4	zcl			
				C	60-					
104	2330176.9	5583963.2		A	0-20	2.5Y 3/2	zl	5.3	0.6	Rb
				AB	20-25	2.5Y 3/3	zl			
				Bw	25-70	2.5Y 5/3	czl			
				R	70-					
105	2337566.0	5579035.5	232.8	A	0-12	2.5Y 3/1	zl	7.5	0.7	Rb
				AB	12-.20	2.5Y 3/1, 2.5Y 5/4	zl			
				Bwk	20-100	2.5Y 6/4	zl			
				BCk	100-120	2.5Y 6/4	zl			
				Ck	120-					
106	2349087.1	5577430.7	104.2	A	0-20	2.5Y 3/1	gzl	4.7	0.4	Tk
				AB	20-25	2.5Y 3/1, 2.5Y 5/6	gzl			
				Bw	25-45	2.5Y 5/6	gzl			
				C	45-					
107	2348651.7	5577179.9	128.6	A	0-15	2.5Y 3/1	gzl	4.2	0.4	Tk
				AB	15-20	2.5Y 3/1, 2.5Y 5/6	gzl			
				Bw	20-40	2.5Y 5/6	gzl			
				C	40-					
108	2333138.2	5582612.4	212.4	A	0-15	2.5Y 3/3	czl	3.7	0.3	Tk
				AB	15-20	2.5Y 5/4	czl			
				Bw	20-50	2.5Y 5/6	gzl			
				C	50-					
109	2333823.8	5582853.2	237.9	A	0-25	2.5Y 3/3	czl	4.4	0.4	Tk
				AB	25-30	2.5Y 4/4	gzl			
				Bw	30-60	2.5Y 6/4	gzl			
				C	60-					

Sample	Easting	Northing	Elev. (m)	Horizon	(cm)	Colour(s), moist	Texture	% C	% N	Soil
110	2336668.2	5584713.7	227.7	A	0-20	2.5Y 3/3	zl	3.2	0.3	Tk
				AB	20-25	2.5Y 4/2	czl			
				Bw	25-60	2.5Y 6/4	gzl			
				C	60-					
111	2336775.9	5583691.4	212.5	A	0-20	2.5Y 3/2	czl	3.3	0.3	Tk
				AB	20-25	2.5Y 3/3	czl			
				Bw(t)	25-95	2.5Y 5/6	gzl			
				C	95-					
112	2335793.6	5587631.7	190.7	A	0-17	2.5Y 3/2	gzl	4.2	0.4	Tk
				AB	17-24	2.5Y 3/2, 2.5Y 5/3	gzl			
				Bg	24-65	2.5Y 5/3, 10YR 5/8	gfsl			
				C	65-					
113	2336162.8	5588092.6	179.9	A	0-17	2.5Y 3/2	gzl	4.6	0.5	Tk
				AB	17-23	2.5Y 3/2, 2.5Y 5/4	gzl			
				Bw	23-33	2.5Y 5/4	gfsl			
				C	33-					
114	2336235.3	5587178.2	185.6	A	0-19	2.5Y 4/2	zl	4.2	0.4	Tk
				AB	19-26	2.5Y 4/2	zl			
				Bt(g)	26-65	2.5Y 5/4	cl			
				BC	65-80	2.5Y 5/4	gcl			
				C	80-					
115	2336545.0	5587119.9	183.5	A	0-19	2.5Y 4/2	zl	3.2	0.3	Tk
				AB	19-26	2.5Y 4/2	zl			
				Bt(g)	26-65	2.5Y 5/4	cl			
				BC	65-80	2.5Y 5/4	gcl			
				C	80-					
116	2332826.5	5586088.0	231.1	A	0-10	2.5Y 3/2	gzl	4.6	0.4	Tk
				C	10-					
117	2331456.9	5586233.0	251.7	A	0-20	2.5Y 3/2	gzl	2.8	0.3	Tk
				AB	20-25	2.5Y 3/3	gzl			
				Bw	25-65	2.5Y 4/3	gzl			
				Bt	65-100	2.5Y 6/4	gzl			
				C	100-					
118	2336114.0	5583575.1	220.4	A	0-15	2.5Y 3/3	czl	2.6	0.3	Tk
				Bw	15-45	2.5Y 3/3	czl			
				C	45-					
119	2333948.5	5583517.3	250.0	A	0-25	2.5Y 3/2	czl	4.5	0.4	Tk
				AB	25-30	2.5Y 4/3	czl			
				Bw	30-95	2.5Y 6/4	fsl			
120	2335362.9	5588220.7	128.0	A	0-17	2.5Y 3/2	gzl	3.3	0.3	Tk
				AB	17-23	2.5Y 4/2	gzl			
				Bw	23-44	2.5Y 4/1	gzl			
				C	44-					
121	2330023.9	5585419.9	263.2	A	0-27	2.5Y 3/2	gzl	3.1	0.3	Tk
				AB	27-34	2.5Y 3/3	gzcl			
				Bw	34-45	2.5Y 4/3	gzcl			
				C	45-					

Sample	Easting	Northing	Elev. (m)	Horizon	(cm)	Colour(s), moist	Texture	% C	% N	Soil
122	2331499.6	5589619.4	117.2	A	0-20	2.5Y 3/2	zl	3.9	0.4	Tt
				Bw	20-70	2.5Y 5/3	zl			
				R	70-					
123	2330505.8	5589488.2	143.4	A	0-20	2.5Y 3/3	zl	3.0	0.3	Tt
				Bw	20-50	2.5Y 5/3	czl			
				2Bw	50-60	2.5Y 6/4	fsl			
				C	60-	2.5Y 5/4	ls			
124	2330411.1	5589367.1	143.3	A	0-20	2.5Y 3/2	zl	3.9	0.4	Tt
				AB	20-25	2.5Y 3/1	zl			
				Bw1	25-108	2.5Y 5/3	zl			
				Bw2	108-	2.5Y 6/4	sl			
125	2330030.8	5589235.6	146.4	A	0-15	2.5Y 3/2	zl	5.8	0.5	Tt
				AB	15-20	2.5Y 3/2//4/2	zl			
				Bw	20-60	2.5Y 4/2	zl			
126	2330433.6	5589409.8	141.5	A	0-30	2.5Y 3/2	zl	4.2	0.4	Tt
				AB	30-35	2.5Y 4/2	zl			
				Bw1	35-50	2.5Y 6/2	zl			
				Bw2	50-120	2.5Y 7/4	cl			
				C	120-	2.5Y 8/4	cl			
127	2331237.3	5589542.0	126.2	A	0-25	2.5Y 3/2	zl	5.1	0.5	Tt
				AB	25-30	2.5Y 5/3	zl			
				Bw	30-80	2.5Y 5/4	zl			
				C	80-	2.5Y 6/3	zl			
128	2330477.3	5589428.1	137.7	A	0-23	2.5Y 8/3	zl	4.6	0.5	Tt
				Bw	23-60	2.5Y 4/4	zl			
				C	60-95					
129	2331551.8	5589564.1	116.7	A	0-40	2.5Y 3/2	zl	5.3	0.6	Tt
				B1	40-60	2.5Y 6/3	zl			
				B2	60-110	2.5Y 6/4	zl			
				CR	110-					
130	2331735.7	5589496.0	113.8	A	0-30	2.5Y 3/2	zl	3.7	0.4	Tt
				AB	30-35	2.5Y 3/2	zl			
				B	35-105	2.5Y 5/3	s			
				CR	105-					
131	2330023.3	5589243.7	148.1	A	0-14	2.5Y 3/2	zl	5.6	0.6	Tt
				AB	14-20	2.5Y 3/2/4/2	zl			
				Bw	20-40	2.5Y 4/2	zl			
132	2348733.4	5577627.4	112.1	A	0-20	2.5Y 3/2	zl	3.6	0.3	Ti
				AB	20-30	2.5Y 6/6, 2.5Y 5/3	zl			
				Bwt	30-60	2.5Y 5/4	zl			
				Bw	60-	2.5Y 6/4	zl			
133	2344471.9	5579158.1	163.4	A	0-15	2.5Y 3/3	zl	4.0	0.4	Ti
				AB	15-20	2.5Y 4/3	zl			
				Bt	20-60	2.5Y 5/4	zl			
				Bw(t)	60-100	2.5Y 6/4	czl			
				Bw(g)	100-	2.5Y 5/6, 2.5Y 6/2	czl			

Sample	Easting	Northing	Elev. (m)	Horizon	(cm)	Colour(s), moist	Texture	% C	% N	Soil
134	2339592.2	5577859.7	168.8	A	0-13	2.5Y 3/2	czl	3.5	0.3	Ti
				AB	13-30	2.5Y 5/4	czl			
				Bw(t)	30-80	2.5Y 5/4	czl			
				Bw	80-110	2.5Y 6/4	fls			
				Bw(x)	110-125	2.5Y 6/4	fls			
				C	125-					
135	2346754.0	5576529.7	169.9	A	0-25	2.5Y 3/2	zl	2.8	0.2	Ti
				AB	25-30	2.5Y 3/2, 2.5Y5/6	zl			
				Bwt	30-90	2.5Y 5/6	zl			
				Bw	90-	2.5Y 6/4	czl			
136	2340119.4	5576032.3	99.3	A	0-15	2.5Y 3/3	zl	3.4	0.3	Ti
				AB	15-20	2.5Y 4/4	zl			
				Bw(t)	20-65	2.5Y 5/6	zl			
				Bt	65-100	2.5Y 5/6	zl			
				Bw	100-	2.5Y 6/4	czl			
137	2347303.5	5577228.5	185.3	A	0-20	2.5Y 3/2	zl	3.5	0.3	Ti
				AB	20-30	2.5Y 3/2, 2.5Y 6/2	zl			
				Bw(t)	30-70	2.5Y 6/2	zl			
				Btg	70-100	2.5Y 7/3, 10YR 5/8	czl			
				Bx	100-130	2.5Y 6/4	czl			
				C	130-					
138	2335292.0	5578924.8	128.5	A	0-10	2.5Y 4/4	zl	3.5	0.3	Ti
				AB	10.-15	2.5Y 5/6	czl			
				Bw	15-40	2.5Y 4/6	czl			
				C	40-					
139	2331722.1	5582484.3	228.3	A	0-5	2.5Y 5/4	zl	3.1	0.3	To
				Bw	5.-50	2.5Y 4/6	fls			
				C	50-					
140	2331758.2	5580814.7		A	0-35	2.5Y 3/2	zl	3.7	0.3	To
				AB	35-40	2.5Y 3/3	zl			
				Bwt	40-120	2.5Y 4/6	czl			
				BC	120-150	2.5Y 5/6	fsl			
				C	150-					
141	2338107.2	5578259.1	176.9	A	0-20	2.5Y 3/1	zl	4.3	0.4	To
				AB	20-25	2.5Y 3/1, 2.5Y 4/4	zl			
				Bw	25-80	2.5Y 5/4	zl			
				C	80-	2.5Y 5/4	fsl			
142	2330797.7	5583471.6	233.8	A	0-30	2.5Y 3/2	zl	7.0	0.7	To
				R	30-					
143	2338179.9	5578381.5	171.6	A	0-20	2.5Y 3/1	zl	4.0	0.4	To
				AB	20-25	2.5Y 2/1, 2.5Y 4/3	zl			
				Bw	25-80	2.5Y 5/6	zl			
				C	80-110	2.5Y 4/6	fsl			
144	2329981.3	5584318.4		A	0-15	2.5Y 3/2	zl	5.7	0.6	To
				AB	15-20	2.5Y 3/3	zl			
				Bw	20-70	2.5Y 4/4	czl			
				C	70-					

Sample	Easting	Northing	Elev. (m)	Horizon	(cm)	Colour(s), moist	Texture	% C	% N	Soil
145	2330677.1	5584920.1	202.2	A	0-15	2.5Y 3/2	zl	4.2	0.4	To
				AB	15-20	2.5Y 3/3	zl			
				Bw1	20-40	2.5Y 5/3	czl			
				Bw2	40-145	2.5Y 6/4	czl			
146	2330325.3	5584727.9	189.8	A	0-20	2.5Y 3/2	zl	3.8	0.3	To
				AB	20-25	2.5Y 3/3	zl			
				Bw	25-85	2.5Y 5/3	czl			
				C	85-					
147	2332657.9	5584969.6	182.3	A	0-20	10YR 2/2	zl	4.1	0.4	To
				AB	20-30	10YR 2/2, 2.5Y 2/4	fsl			
				Bwt	30-80	2.5Y 5/6	fsl			
				Bw(g)	80-135	2.5Y 6/4, 2.5Y 7/3	fsl			
				C	135-					
148	2332444.3	5584891.2	191.8	A	0-15	10YR 3/1	zl	4.8	0.4	To
				AB	15-20	10YR 3/1, 2.5Y 4/6	fsl			
				Bwt	20-80	2.5Y 4/6	fsl			
				BC	80-130	2.5Y 5/6	fsl			
				C	130-					
149	2337693.4	5579042.3	210.5	A	0-15	2.5Y 2/1	zl	5.0	0.5	To
				AB	15-35	2.5Y 4/6, 2.5Y 3/1	zl			
				Bw	35-100	2.5Y 5/6	zl			
				BCk	100-140	2.5Y 4/6	zl			
				Ck	140-					
150	2337136.4	5579203.5	204.7	A	0-15	2.5Y 3/2	zl	5.0	0.5	To
				AB	15-20	2.5Y 3/1, 2.5Y 4/3	zl			
				Bw	20-60	2.5Y 4/4	zl			
				C	60-	2.5Y 4/6	zl			
151	2337883.9	5578886.2	216.9	A	0-25	2.5Y 2/1	zl	6.2	0.6	To
				AB	25-30	2.5Y 2/1, 2.5Y 3/3	zl			
				Bw	30-90	2.5Y 4/4	zl			
				C	90-					
152	2337487.0	5579289.6	177.5	A	0-20	2.5Y 3/2	zl	4.9	0.4	To
				AB	20-25	2.5Y 3/2, 2.5Y 4/4	zl			
				Bw	25-80	2.5Y 4/4	zl			
				Bwk	80-120	2.5Y 4/6	zl			
				BCk	120-145	2.5Y 6/6	zl			
				Ck	145-					
153	2337726.2	5578693.7	241.5	A	0-15	2.5Y 3/2	zl	4.5	0.4	To
				AB	15-20	2.5Y 3/2, 2.5Y 4/3	zl			
				Bw1	20-100	2.5Y 6/4	zl			
				Bw2	100-190	2.5Y 6/4	ls			
				Bwx	190-250	2.5Y 6/4	ls			
				BC	250-275	2.5Y 5/4	ls			
154	2337774.8	5578650.8	241.4	A	0-15	2.5Y 3/2	zl	4.1	0.4	To
				AB	15-20	2.5Y 3/2, 2.5Y 4/6	zl			
				Bw1	20-100	2.5Y 5/6	zl			
				Bw2	100-	2.5Y 5/4	ls			

Sample	Easting	Northing	Elev. (m)	Horizon	(cm)	Colour(s), moist	Texture	% C	% N	Soil
155	2337918.5	5578463.4	225.0	A	0-15	2.5Y 3/2	zl	3.9	0.4	To
				AB	15-20	2.5Y 3/2, 2.5Y 5/6	zl			
				Bw1	20-90	2.5Y 5/4	zl			
				Bw2	90-	2.5Y 6/6	ls			
156	2337743.8	5578615.2	238.6	A	0-15	2.5Y 3/2	zl	4.7	0.5	To
				AB	15-20	2.5Y 3/2, 2.5Y 4/6	zl			
				Bw1	20-90	2.5Y 5/6	zl			
				Bw2	90-130	2.5Y 5/6	ls			
157	2337632.6	5577805.0	239.5	A	0-15	2.5Y 3/2	zl	4.3	0.4	To
				AB	15-20	2.5Y 3/2, 2.5Y 4/4	zl			
				Bw1	20-50	2.5Y 4/4	zl			
				Bw2	50-	2.5Y 5/6	ls			
158	2334744.4	5579057.6	148.7	A	0-15	2.5Y 3/3	zl	4.6	0.4	To
				AB	15-20	2.5Y 4/6	czl			
				Bw	20-60	2.5Y 4/6	czl			
				C	60-					
159	2333411.4	5576508.4	128.1	A	0-10	2.5Y 4/4	czl	2.5	0.2	To
				AB	10.-15	2.5Y 4/6	czl			
				Bw	15-80	2.5Y 5/6	fsl			
				C	80-					
160	2336709.9	5575978.6	86.1	A	0-30	2.5Y 3/3	czl	4.1	0.4	To
				AB	30-35	2.5Y 3/3, 2.5Y 7/4	czl			
				Bg	35-100	2.5Y 6/2, 5YR 4/8	fsl			
				C	100-					
161	2335500.5	5578016.1	132.3	A	0-15	2.5Y 3/3	czl	3.4	0.3	To
				AB	15-20	2.5Y 4/4	czl			
				Bw	20-70	2.5Y 4/6	czl			
				C	70-					
162	236617.85	5575881.3	80.1	A	0-15	2.5Y 3/3	czl	5.3	0.5	To
				AB	15-20	2.5Y 4/4	czl			
				Bw	20-80	2.5Y 5/6	fsl			
				C	80-					
163	2335478.4	5578844.9	118.3	A	0-12	2.5Y 4/4	zl	3.1	0.3	To
				AB	12.-15	2.5Y 5/6	czl			
				Bw	15-50	2.5Y 4/6	czl			
				C	50-					
164	2333067.3	5585330.8	197.7	A	0-10	2.5Y 4/4	fsl	3.1	0.2	To
				Bw	0-50	2.5Y 5/4	fsl			
				C	50-	2.5Y 5/6	fsl			
165	2332490.9	5584127.6	206.4	A	0-15	2.5Y 3/3	zl	2.9	0.3	To
				AB	15-20	2.5Y 4/3	zl			
				Bw	20-	2.5Y 5/4	czl			
166	2337199.7	5578761.8	175.7	A	0-30	2.5Y 3/2	czl	5.2	0.5	To
				AB	30-35	2.5Y 3/3	czl			
				Bw	35-60	2.5Y 4/6	czl			
				C	60-					

Sample	Easting	Northing	Elev. (m)	Horizon	(cm)	Colour(s), moist	Texture	% C	% N	Soil
167	2338137.4	5577584.1	156.7	A	0-15	2.5Y 3/2	czl	3.5	0.3	To
				AB	15-20	2.5Y 3/3	czl			
				Bw	20-70	2.5Y 4/6	czl			
				C	70-					
168	2336600.8	5578791.3	319.3	A	0-25	2.5Y 3/3	czl	3.9	0.4	To
				AB	25-30	2.5Y 4/2	czl			
				Bw(R)	30-45	10YR 5/8, 2.5Y 6/4	czl			
				Bw(t)	45-	2.5Y 5/4	fsl			
169	2337012.6	5578589.6	138.0	A	0-25	2.5Y 3/2	czl	4.4	0.4	To
				AB	25-30	2.5Y 3/3	czl			
				Bw	30-100	2.5Y 4/6	czl			
				C	100-					
170	2332104.1	5585036.8	188.2	A	0-30	2.5Y 3/2	czl	3.6	0.4	To
				AB	30-35	2.5Y 3/2, 2.5Y 5/6	czl			
				Bwt	35-80	2.5Y 5/4	czl			
				Bw(g)	80-120	2.5Y 6/3, 2.5Y 6/6	fsl			
				BC	120-150	2.5Y 5/6	fsl			
				C-	150-					
171	2332627.0	5585474.0	220.9	A	0-20	2.5Y 3/3	zl	3.9	0.4	To
				Bw	20-90	2.5Y 4/4	czl			
				BC	90-	2.5Y 4/4	czl			
172	2332546.0	5583996.5	236.8	A	0-45	2.5Y 3/3	zl	4.4	0.4	Wk
				AB	45-50	2.5Y 3/3	zl			
				Bwt	50-70	2.5Y 5/4	czl			
				R	70-					
173	2331029.4	5584916.6	230.1	A	0-15	2.5Y 3/2	zl	3.7	0.4	Wk
				AB	15-20	2.5Y 4/3	zl			
				Bw	20-90	2.5Y 5/4	czl			
				BC	90-130	2.5Y 6/4	czl			
				C	130-					
174	2330117.4	5589235.7	152.5	A	0-20	2.5Y 3/2/3/3	zl	5.8	0.5	Wk
				B1	20-56	2.5Y 5/4	zl			
				B2	56-	2.5Y 5/4	zl			
175	2333977.7	5587305.6	194.1	A	0-24	2.5Y 3/2	zl	3.2	0.3	Wk
				AB	24-30	2.5Y 3/2	zl			
				Bw	30-45	2.5Y 5/3	czl			
				Bt	45-70	2.5Y 5/3	czl			
				Bw2	70-90	2.5Y 5/4	czl			
				R	90-					
176	2333235.5	5587838.2	161.5	A	0-20	2.5Y 3/3	zl	6.2	0.6	Wk
				AB	20-25	2.5Y 4/2	czl			
				Bw	25-70	2.5Y 5/3	czl			
				Bt	70-85	2.5Y 6/3	czl			
				Bw2	85-120	2.5Y 7/4	fsl			
				BC	120-	2.5Y 6/4	czl			

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